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System Dynamics and Process Improvement: Can the U.S. Navy Acquisition Community Learn from Industry Behavior?

by

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Submitted to the Alfred P. Sloan School of Management and
the School of Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Science in the Management of Technology

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Abstract

System dynamics is a powerful management planning tool for process improvement programs. Industry experience has contributed to a model that allows decision makers to simulate their actions and the resulting system response before committing to the actual policies. The resulting understanding of fundamental system behavior and interactions allows more productive and effective decision making and process improvement. Application of such a tool for U.S. Navy major acquisition programs (e.g., ships and submarines) would be invaluable in terms of cost savings, cost avoidance, schedule reductions and overall efficiency improvement.

This effort conducts a review of the Science and Technology (S&T) portion of current Navy acquisition policies as a case study. The feasibility of applying the Navy system behavior to the existing MIT System Dynamics Group Simulation for Continuous Improvement Programs (SCIP) "management flight simulator" and model will be presented. This work will contribute to the ongoing efforts of MIT system dynamics research as well as the Navy acquisition reform initiatives.

Thesis Supervisor: John D. Sterman
Standish Professor of Management

Acknowledgements

As with all projects that set out to explore new frontiers, this thesis journey was not an individual effort. I had the opportunity and pleasure of working with many people from academia, industry, and government. Without their support and willingness to listen, offer insight, at times object, and to engage and challenge me in the problem at hand, this thesis would not have been possible.

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To the entire class of MOT 1999—you are the best. May we continue our separate journeys through life but meet often for reflection and growth—Navy Bill.

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1.0 Introduction

1.1 Issue Statement

The capital assets of the U.S. Navy are expensive. Large scale research and development (R&D), design, construction, test and evaluation, delivery, operation, maintenance and repair, and ultimately disposal of ships, submarines, and aircraft cost the taxpayers billions of dollars. From a distance, many characterize the acquisition process as a chaotic dance of politics, random actions and knee-jerk responses. These characterizations could, at times, also be applied from the perspective of those stakeholders that work within the current system. Why is this the case?

It is not for lack of effort by competent groups and individuals that this view is commonplace [Ryan and Jons 1991]. Perhaps the mere complexity of the process precludes a clear understanding of the policy actions and resulting responses that reside within the current system. Sterman has illustrated that learning and understanding in highly complex systems are at the very least significant challenges to organizations and individuals [Sterman 1994]. Much effort has been expended in trying to understand the "driving forces" behind personnel behavior and impacts of policy actions. Specific improvement recommendations range from enhancing communication among the decision makers [Bennet 1998], to better understanding the practices of the existing shipbuilder infrastructure [McCue 1997], to concentrating on the ship design methodology [Laverghetta 1998]. More broadly, Roberts' global benchmarking study has shown that, as a result of complex industrial practices, policy implementation, and established functionality; more than fifty percent of the world-wide product development projects experience cost overruns and schedule delays [Roberts 1992]. Others have attempted to quantify the

action/reaction feedback, delay times, and nonlinear cause and effect relationships between various elements of project teams [Ford 1995].

Each of these efforts covers a range of project development issues and contributes to better understanding general processes and scenarios, but none address the particular aspects of the current Navy acquisition process. Failure to identify "*the answer*" should not, however, dissuade policy makers from attempting to do something to improve the status quo. No single model or solution set could reasonably be expected to "solve" such a complicated system. Nevertheless, there are several encouraging areas of thought that can be explored as a means to, at a minimum, generate and communicate more clearly the key behaviors of the acquisition process.

In the face of increasing domestic and global competition, U. S. industry has experienced both success and failure in implementing sustainable process improvement efforts. Many of the behaviors, decisions, and interactions involved in several improvement programs have been captured at the systems level and developed into an extensive computer simulator—the Simulation for Continuous Improvement Programs [Repenning, *et al.* 1998].[1]

A better understanding of the Navy acquisition *system* may be gained from extensive industry experience in process improvement. By drawing parallels with the fundamental behaviors found in successful business improvement initiatives, along with understanding the pitfalls experienced in less successful efforts, enhancements to the Navy acquisition process may be approached more systematically. The concepts presented here lend support to the manner in which lessons

from business can be used to make timely and significant enhancements to Navy capital acquisition programs.

1.2 Current Practices

The complexity of modern ship design and construction projects is truly astonishing. Ships, once simply timbers, sails and cannons, have evolved into floating self-sufficient cities providing home, office, factory, hospital, recreation facility, restaurant, airport, computer network, satellite communication suite, life support, and offensive and defensive weapons systems on a mobile platform that travels the globe on command. These systems are as complex as any manmade project on land or in space. The development and coordination of such programs are anything but common or repeatable, yet commonality and repeatability could very well enhance the efficiency of current and future projects—if the effort is properly understood and managed.

Developing a platform architecture around standardized common components and interfaces greatly reduces development time while simultaneously creating a path for an array of customized and reconfigurable designs [Meyer and Lehnerd 1997]. Establishing these common features would enable multiple platforms to share proven, tested, and certified technologies without having to redesign similar components for each new application. As an example, current Navy practices develop ship and submarine programs independently with scarcely any common systems [Brougham, *et al.* 1999]. Since many functional requirements are shared by both platform types, a Navy wide program of common interfaces and systems would allow much

[1] The original name of the model has been changed from the "Continuous Improvement Program Learning Laboratory (CIPLL)" to the "Simulation for Continuous Improvement Programs (SCIP)." The later will be used throughout the thesis.

more synergy between existing and future performance needs. In the ultimate integrated program architecture, these interfaces would be common across all applicable Department of Defense (DoD) systems and similar to commercially available products such that the government could experience a significant cost savings. This is known as using commercial-off-the-shelf (COTS) technology and is in direct competition with the longstanding practice of using "legacy" systems. Legacy systems are those systems and components with a history of use and proven performance that have evolved over time on an individualized platform by platform basis without regard for cost efficiency. By understanding the interfaces and overall architecture of such systems, concurrent development of system enhancements and technological improvements could exist while in-service systems continue to function in the fleet.

The concurrent development is only feasible, however, if conducted at a systems level with wide applicability [Eppinger, *et al.* 1994]. This methodology requires fewer large scale, hugely expensive, new projects at the ship-wide level. It facilitates smaller, more affordable, and more manageable projects on a system-by-system basis. The component costs for this performance—under the common architecture and interfaces logic—could, however, be significantly less than traditional legacy system performance upgrades [Meyer and Lehnerd 1997].

The common platform architecture has far reaching impact for increasing the performance value of the Navy acquisition process. A significant element for the success of this concept hinges upon the willingness of decision makers to except the risk of changing current practices—clearly no small undertaking. This argument has striking similarities to the challenges encountered by an established firm producing a mature product when faced with an innovative technology or

competing product entering the market place. In this situation, the new entrant often displaces the established firm from the marketplace [Utterback 1994]. Complementary illustrations highlight that it is precisely this scenario that would make it possible for the Navy acquisition community to succeed if they adopted innovative new methodologies. At the component level, the new technology would be the Navy application of a COTS system to replace a legacy system developed solely for government application. At a more system-wide level, the process innovation for the Navy would be adoption of industry "best practices" and process improvement experience to support, improve, and/or replace the traditional DoD acquisition practices. Such is the current motivation and intent of DoD acquisition reform initiatives sweeping the government. The more common equivalent to this analysis is that of a "disruptive technology" [Christensen 1997] wherein the newer entrant often dominates the market with a product or process that another firm may have originated. Even more critical to this discussion, is the fact that the eventual dominating firm often uses the disruptive technology in a manner that it was not originally intended—defense system project acquisitions and technology development vice business manufacturing and product development initiatives. This research will attempt to bridge the disruption gap in acquisition reform by employing lessons from industry process improvement initiatives to the Navy process.

1.3 Dynamic Modeling of the Process Improvement Process

The notion of process improvement is clearly not isolated to the leaders of the Navy acquisition process. Industry has been involved in one form or another of process change for as long as businesses have existed. Yet, due to the complexity of most processes, most efforts have unforeseen and sometimes disastrous outcomes. Many process improvement programs (PIPs)

are implemented based on the manager's mental model[2] of the existing process and the perceived interactions that take place between relevant components of the organization. The initial results of PIP initiatives are many times successful in that they appear to reinforce the change in system performance that was intended. Despite these early benefits, however, many initially successful efforts degenerate and some end up causing harm to the company [Repenning and Sterman 1997]. The reason for the transition from success to failure often stems from the quality and robustness of the original mental model, which usually fails to include all of the necessary secondary and tertiary feedback effects and endogenous variable relationships [Sterman, *et al.* 1997]. In implementation, the uncertainty of sustaining continued success for a seemingly beneficial PIP highlights the need to overcome the "Improvement Paradox" [Keating, *et al.* 1994]. The paradox has been repeatedly shown to result from management's inability to understand the dynamic nature of the improvement program they impose upon their organization. Inability is by no means due to negligence, but is a result of the inherently complex nature of dynamic systems. This lack of understanding is to a great extent mitigated through extensive computer modeling and simulation [Repenning 1997].

In an ongoing effort within the MIT System Dynamics Group, four major U.S. companies' process improvement programs have been studied in great detail and a common dynamic computer model has been created that emulates the results of each PIP [Repenning, *et al.* 1998]. The Simulation for Continuous Improvement Programs (SCIP) model has evolved from earlier work with Analog devices, Inc. [Sterman, *et al.* 1997]. The work was originally supported with the aid of a grant form the National Science Foundation as well as participation by the involved

[2] A *mental model* is a conceptual understanding of the behaviors relevant to a given system. This term is frequently used in the field of System Dynamics.

industries. In developing the extensive model and management simulator, multiple interviews with executives, managers, and employees from such functional specialties as operations, human resources, customer service, and product development were conducted. The resulting data addressed such varied areas as financial performance, defect rates, customer satisfaction, and employment issues [McPherson 1995].

The model addresses multiple dimensions of the process improvement challenge. It is one part of a complete management decision making tool that includes a "management flight simulator" for demonstrating the effect that various PIP decisions would have on the firm. This powerful tool allows decision makers to better understand the impact of their actions over a longer time horizon. In other words, the computer model permits a manager to further develop their mental model and bring it more in line with the fundamental policy results underlying their decisions. Simulation attempts to avoid the improvement paradox by developing a more thorough understanding of the feedbacks, delays, and interactions within a company. In addition, the simulation promotes a better understanding of which relationships are the high leverage points from which to enact improvement. Simulation avoids costly and frustrating PIP policy changes that are short term in nature and allow for a more focused effort which has a much higher potential of succeeding over a longer period of time. In short, the dynamic model facilitates more robust managerial decision making through process improvement policies that result in their intended goal and in a sustainable fashion.

1.4 Motivation and Approach

This thesis will attempt to assess the current Navy acquisition process improvement initiatives [Acquisition Center of Excellence 1998] by performing an original analysis of the existing process [Keller 1997]. The case study will investigate the high leverage points and relate potential innovative technologies and policies (as discussed in section 1.2) to the SCIP management simulator and model. The framework will suggest how the Navy acquisition process can be better understood and enhanced by applying an existing dynamic model of actual process improvement efforts in such varied industries as: a printed circuit board manufacturer, a recreational products manufacturer, an automobile electronic components manufacture, and a semiconductor manufacturing firm [Repenning, *et al.* 1998]. Successful mapping of a new process from a significantly different business sector—the Navy—into the existing model space will contribute to the Navy acquisition process improvement initiatives as well as enhance confidence in the SCIP model. The added fidelity in the computer simulation could then be translated into the management flight simulator and training program furthering the dynamic modeling effort within the process improvement arena. Additional work could then be performed with relevant Navy decision variables in customizing the format of the model and training program for use in improving management decision tools for U.S. Navy acquisition programs.

A better and more accurate understanding of the current process would allow leaders to use available technologies in an innovative fashion and take the "right" steps toward process improvement. In the process, this would dispel the original classification of the entire Navy acquisition process. The resulting change would be re-characterized as a *choreographed* dance

of *clear policies* enacted through *coherent decisions*. This is a far superior method of organizational management than the *chaotic* behavior and *political* drifting that stems from *random actions and knee-jerk responses*.

2.0 System Dynamics and Process Improvement

2.1 System Dynamics Overview

The field of system dynamics was developed by Jay Forrester at MIT in the 1950's with the stated goal "...to create more successful management polices and organizational structures." [Forrester 1961]. To fulfill this goal, managers must first articulate their mental models of system behavior and understand the implications and limitations of these models relative to reality. More often than not, these mental models are incomplete representations of the real system's behavior and represent only that portion of a system that is known or perceived as relevant by the individual manager. Each person has his or her own understanding of the important interactions. In complex systems, there are many secondary and circular feedback interactions that hamper a clear understanding of behavior. These effects are most often unrecognized because they are usually delayed from the initial cause and difficult to relate back to a particular action, decision, or event. System dynamics provides a method for expanding mental models, the inherent delays, and the feedback effects. By expanding one's mental model, so too is expanded the awareness of a system's behavior. Awareness then leads to better decision making and ultimately—*more successful management policies and organizational structures*.

The clearest method of conceptualizing the above discussion is via illustration. The following example, though extremely simplistic, is a very useful and compelling. Consider a fable of the

chicken and the egg.[3] The size of the population of chickens is influenced by the number of eggs. The quantity of eggs is determined by the size of the chicken population. The size of one quantity reinforces the size of the other. This is shown pictorially as a causal loop[4] in Figure 1.

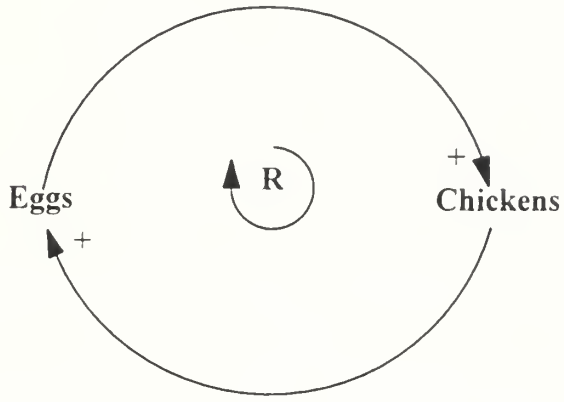

Figure 1: Reinforcing Loop

The reinforcing behavior is a positive feedback effect that, over time, would cause the chicken population to grow exponentially. Since we know that this single reinforcing loop is only a part of our mental model, we also recognize that our world is not overrun by chickens so there is more to the dynamics of this system. A population control loop must be included. Figure 2 includes the original reinforcing loop with the addition of a negative feedback loop. The behavior of this loop balances the size of the chicken population with the propensity for chickens to cross the road.

[3] This illustration was inspired by the work of Sterman as the most concise means to portray many aspects of system dynamics [Sterman 1998].

[4] *Causal Loop* is a system dynamics notation method to represent system parameters. The loops can be either reinforcing (R) or balancing (B), corresponding to positive or negative feedback processes, respectively. The arrow notation points from the cause variable to the effect variable.

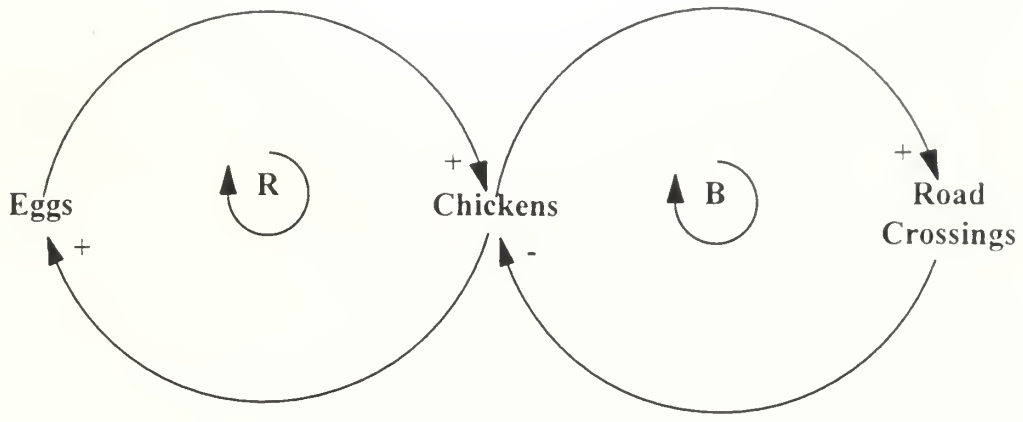

Figure 2: Addition of a Balancing Loop

As the number of chickens increase, the number crossing the road also increases to a value more than it would have been otherwise with all other system parameters held constant. This balancing loop limits the growth of the chicken population because more road crossings reduce the chicken population.

2.2 Power and Criticism of the Method

Again, it is recognized that this illustration is very simple but the significance of the example is far reaching. Figure 2 highlights both the *power* and the *criticism* of the system dynamic method. The causal loops in Figure 2 do not include *all* of the necessary loops or behaviors. A critic of the method would demand additional loops for coyotes, hunters, and countless other sources of mortality for the balancing effects. Their mental model would resemble that shown in Figure 3.

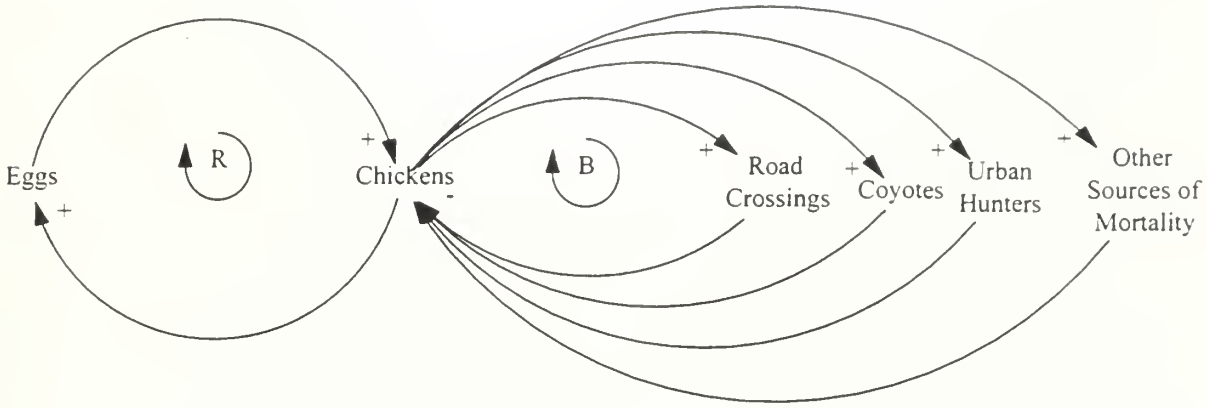

Figure 3: Multiple Balancing Loops

Each additional loop adds either a balancing or reinforcing loop, although in this example above only balancing loops are considered. The dominance of any loop can vary and be influenced by external variables (i.e., the coyote population is itself influenced by a similar structure as the overall chicken and egg loop). Since the two loop structure of Figure 2 does not include the additional loops of Figure 3, then it must clearly be wrong. In fact it most certainly is wrong, but is the more complex structure right? The answer is no, because Figure 3 is not a "complete" picture of the chicken world. There are an unlimited number of additional balancing loops that could be linked, some more strongly than others, to the decline of a chicken population. Including the minutia of detail does not add to the basic concept of the chicken and egg dynamic, however. This illustration reinforces the idea that *all models are wrong*. Nevertheless, good models remain useful, despite being wrong.

The power of system dynamics is that such simple representations of more complex systems can still be quite useful in understanding a system's fundamental behavior. If a more detailed analysis or understanding is necessary then additional loops can be explored and added to the basic model without invalidating the underlying structure. Consider, for example, "road

crossings" as the "net cause of chicken deaths." Then the more complex representation of figure 3 could still be presented as in the original, more simplified Figure 2.

The Navy acquisition process is an extremely complex system and prior system dynamics efforts have perhaps fallen into the trap of oversimplification [McCue 1997 and Laverghetta 1998]. By trying to model large portions of the overall system, the power of simplification can be blurred with maintaining enough detail of the essential system elements to accurately characterize the overall system's behavior. Some models include only the observable quantity of behavior loops and do not look at an overall system response level. Making policy decisions on this scale can sometimes lead to undesired and unanticipated effects.

2.3 Simulation for Continuous Improvement Programs Model

The SCIP is a system dynamics education and training tool designed to provide managers the necessary understanding of how their decisions impact the broader system. It is built around the experience of four different manufacturing companies and their lessons in process improvement initiatives. Data assembled from a variety of sources was integrated into a single model over a period of several years within the MIT System Dynamics Group. The effort created an extensive computer simulation model that can be used to simulate specific policy decisions over time. From the original model, a management flight simulator was developed to address four specific process improvement initiatives [Repenning *et al.* 1998]:

1. Printed Circuit Board Manufacturer—Original system relied upon extensive quality control checks and testing to ensure delivered products were of high quality. This

program generated extensive scrap rates and cost. An improvement initiative was begun to increase labor productivity and manufacturing yield to lower the overall costs associated with high labor content operations. The results did improve the stated goal but did not translate to a higher demand since cost savings were quickly matched by the competition. The unanticipated side effect was that the increased productivity and stable demand incited labor force reductions and resentment over future improvement efforts.

2. Recreational Products Manufacturer—A long standing product dominance and lack of competition was accompanied by declining quality. Eventually, competitors entered the market with higher quality products and captured a substantial share of the industry. A production quality improvement effort was put in place to close the quality gap and regain market share. The improved quality regained a major portion of the now expanding market, but was accompanied with increasing prices which alienated the existing customer base.

3. Electronics Components Manufacturer—In an effort to increase competitive performance, a highly successful manufacturing yield improvement effort was enacted. The workers were committed to the effort and devoted a substantial part of their effort to improving quality. The increased production efficiency resulted in underutilized and idle capacity. This resulted in excess overhead costs. The same improvement initiative philosophy was employed in the product development program with the goal of increasing new product deliveries and again increasing the labor and facility utilization of

the now more efficient production capacity. Again, labor commitment was high, but the product development initiative never materialized in increased number of new products.

4. Semiconductor Manufacturer—The market leader in a small niche of the Application-Specific Integrated Circuit (ASIC) market began a program to increase yield, reduce cycle time, and increase labor productivity. The improvement initiative was dramatically successful and resulted in a doubling of yield and significant cost reductions. Despite these results, profitability fell sharply and resulted in large scale labor reductions. The labor commitment to future improvement programs was viewed as a means to improve themselves out of a job and was minimal.

These examples all demonstrate the significance of unanticipated side effects inherent in any complex system. Though many appeared to be successes in the short run, the improvement initiatives in fact burdened future performance. The SCIP management flight simulator is organized around case modules for each of the four scenarios above. The flight simulator allows "What If ...?" analyses to try new policy decisions and observe their short and long-term impacts. The simulator is calibrated for the specific scenario being evaluated and represents the actual results from the real companies. As a training tool, this form of simulation is compelling and could potentially be applied to other manufacturing and product development process improvement efforts. Such is the focus of this research.[5]

[5] For additional details about the SCIP simulator and model, contact the MIT System Dynamics Group.

3.0 Case Study of the Current Navy Process

3.1 Method

Unlike previous Navy acquisition process system dynamics analyses, this research pursues an alternate path. Instead of developing a new partial model of a complex system, I will evaluate a comprehensive model that has been proven useful, insightful, and relevant to decision making in several manufacturing and product development process improvement industries. I will relate a small portion of the large model to a small portion of the Navy acquisition system. In so doing, I hope to show the utility of such a fit and provide motivation for a larger scope initiative to continue to expand the Navy system into other portions of the industry model. At the same time, if such a fit proves impractical, however, this observation will itself be relevant. This logic is quite different from prior system dynamic efforts with the Navy acquisition process. I assert that the comparison of the Navy practices with industry experience could lead to a "best practices" understanding of proven industry policy decisions. This would provide the Navy with an extremely powerful tool for training program managers about the impact of their decisions on the overall system. Such understanding would be able to include how external factors influence a specific manager's environment and how to respond to these factors.

Though this approach lacks a complete analysis of the entire system, it is not without merit. Oliva highlights the importance of understanding partial solutions in an effort to further expand existing mental models [Oliva, *et al.* 1998]. Firms cannot generally wait for the complete solution and answers to every plausible question when faced with the need to make improvements. By embarking on one improvement program, while planning for the next, an

organization can identify common characteristics across multiple improvement efforts. These characteristics may then lead to more complete knowledge of the firm's behavior and, more importantly, encourage subsequent improvement initiatives to utilize the high leverage elements of the organization.

3.2 Navy S&T and the SCIP Model

Data collection for the Navy acquisition process followed a lengthy period of discovery and interviews with various Navy leaders. Initially, effort was focused on the SCIP model to gain a better understanding of the structure of the model. To test the hypothesis of the viability of applying the existing SCIP model to the Navy system, a portion of the model had to be small enough to serve as a manageable test case and significant enough to lend credibility to the analysis.

The production and product development (Production/PD) sub-model was chosen for further analysis. The rationale for this selection was fourfold. Firstly, this portion of the model addresses an area of great interest to the author—Science and Technology (S&T). S&T is the stage of new product development immediately preceding and then transitioning to Research, Development, and Engineering (RD&E) (a more detailed explanation of Navy S&T follows in the next section). Secondly, the size of the SCIP model specifically addressing the initial phases of product development was manageable in scope. The logic here is to select a model segment which can help illustrate the feasibility, or lack thereof, of actually making the overall SCIP model and flight simulator a more developed training aid within the Navy's acquisition community. Another necessary facet of the selection process was access to data. Though this

research only presents a feasibility analysis for the existing model structure, enough data was needed to define the observable trends in system behavior. Finally, the relationship to the topic as a principle effort of the Office of Naval Research (ONR) made the S&T analogy particularly compelling. The final rationale was actually a fortuitous event since this research is in part sponsored by that organization. ONR did not influence the discussion and analyses that follows, however.

3.2.1 Overview of the Navy S&T Process

Science and Technology are the components of the Navy acquisition process that try to anticipate and address the gap that develops between system requirements and technological capability. The requirements stem from Navy tactical and programmatic issues that specify some performance level for a variety of ship performance characteristics. Since the world continues to become more technologically advanced, the requirements for new Naval and DoD systems also evolve to higher and higher performance levels to counter the more advanced threats of the future. If the existing state of the Navy systems remains constant, a gap is created between the demands of the new system—the requirements—and the supply capacity of existing technology—the current stock of completed S&T projects that have not obsolesced since completion. This gap is shown in causal loop diagram of Figure 4 at the top of the figure as the Requirements—Technology Gap.

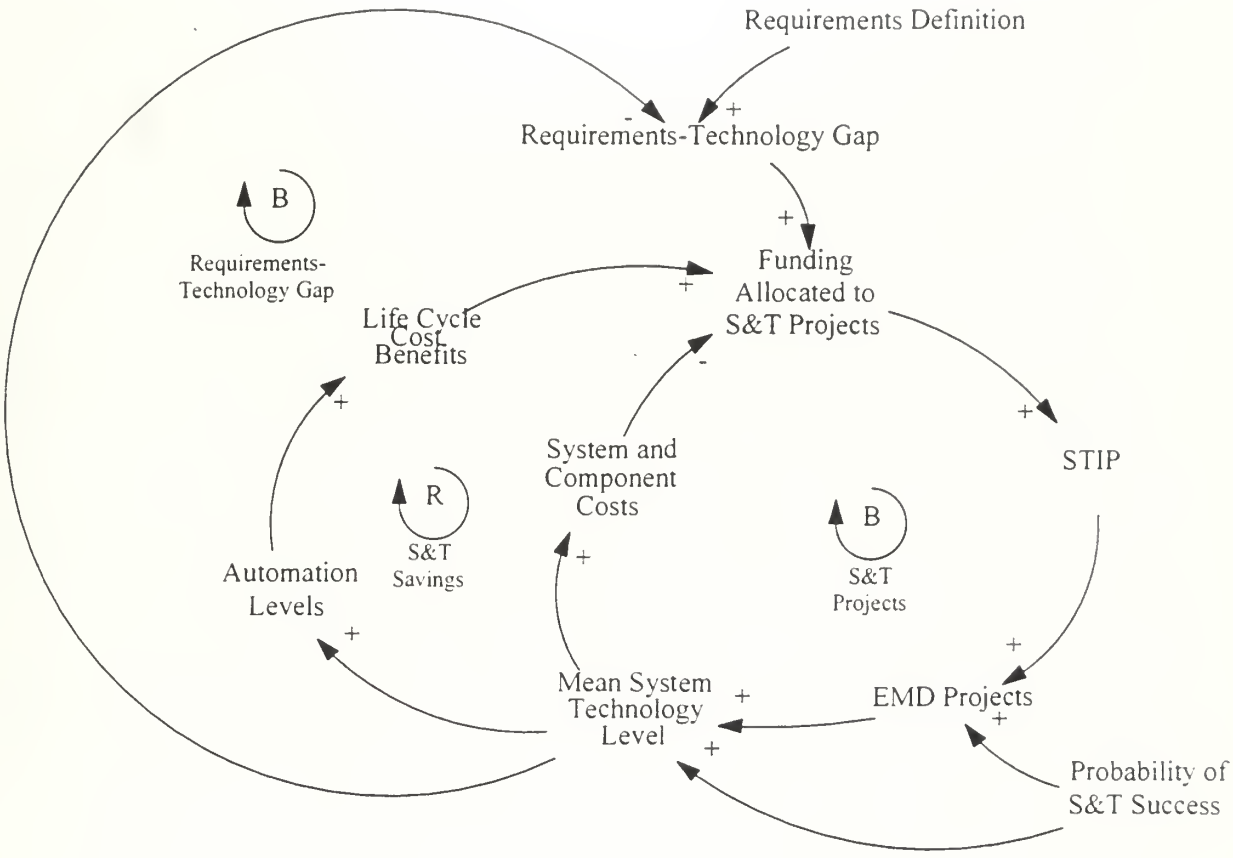

Figure 4: S&T Causal Loop Diagram

Also shown in Figure 4 are three generalized behavior loops relevant to the S&T project system. In the "S&T Projects" balancing loop, the increased gap leads to an increased emphasis on the need for S&T projects. This is communicated to the S&T community via increased funding for S&T projects. As the funding increases the stock of S&T In-Process (STIP) is increased to a level greater than it would have been otherwise. As these projects are completed, some lead to successful new products or systems and others are either cancelled, for a variety of reasons (i.e., politics, allocation of scarce resources, technical difficulties, etc.) or go on to further development. Once a technology has been identified as viable, it then transitions to further analysis called the Engineering, Manufacturing and Development (EMD) phase S&T. At this stage, the laboratory "bench top" system is put through more rigorous testing to ensure the

resulting components are tolerant for use in a military application. During EMD, the laboratory system is engineered to: withstand shock, adverse heat and corrosive atmospheres; demonstrate sufficient reliability and fault tolerance; interface with the systems in the context for which the new technology will be utilized; and a variety of other demands that are requisite in a warship or military system. Since not all new S&T projects meet with useful innovations, the transition from STIP to EMD is represented as a percentage of completed STIP. As more EMD projects are pursued, the technology of available systems increases and with it so too does complexity increase. The added complexity and "newness" of a breakthrough in technology tends to increase the costs for the lead user in actually obtaining the new system. The increased system costs places a downward pressure on the funding allocated to future STIP since the presence of successful STIP and EMD would otherwise continue to increase system complexity and costs. The resulting closed loop is a negative feedback loop. As the Requirements—Technology Gap increases, the funding allocated to S&T increases and the number of S&T projects underway increases. A portion of the increased STIP then leads to increased EMD and increased system complexity. The cutting edge technologies add cost to the projects that choose to use the new systems and, if actually used, force decisions makers to reallocate a finite budget thereby reducing the funding available for additional STIP.

At the same time, the increased system complexity from STIP and EMD raises the level of existing technology and closes the Requirements—Technology Gap. The "Requirements—Technology" balancing loop of Figure 4 shows how closing the gap reduces the motivation for additional STIP initiatives.

Were this the only impact of S&T projects, then they would dwindle in importance. The presence of the reinforcing loop, however, helps to explain the significance of S&T. As previously stated, as more EMD is completed from the STIP pipeline, then the level of system technology is raised. The advanced frontier for state of the art technologies often manifests itself as a higher level of automation and processing. This is demonstrated in industry and the Navy alike as technologies are replacing human operations. Less human involvement in system operations often translates into lower recurring costs. When one considers that many Navy systems are used for thirty or more years, the overall cost savings for human labor reductions dramatically reduces the overall costs for program. The increased use of technology, which originates from the S&T effort, provides life cycle cost benefits which in turn encourages more investment in additional S&T.

The three loops oppose one another. Another way to present the interaction is to talk about fixed versus variable costs. If one considers STIP as an investment in advancing the state of the art and closing the technology gap, then these costs, once allocated, are fixed and therefore an immediate negative influence on the bottom line. The downstream benefits of the investment, however, could lead to significant reductions in the recurring operating costs. As long as the reductions in the variable costs outweigh the size of the initial fixed costs, then more improvement initiatives would be encouraged.

S&T is the Navy's method of investing in new technology development with the goal of achieving downstream benefits and cost reductions. The long term cost reductions are necessary in the face of declining defense spending but, at the same time, the new S&T expenditures are

necessary in a world of increasing technological complexity. The simplified representation of some of the influencing factors on Navy S&T is useful for discussion, but lacks the detail necessary to better understand the dynamic behaviors within the system and thus allow clear policy decision analysis. The ability to test hypotheses and scenarios would be exceptionally useful to Navy leaders, project managers, and Congressional decision makers. In order to accomplish such tests, a more mathematical representation of the S&T dynamic is required. With that, a better understanding of the specific details driving the high level variables shown in Figure 4 is required. Let us now look to a portion of this causal loop structure in more detail.

3.2.2 Relating the SCIP Model to the Navy S&T Process

As discussed above, the SCIP model represents a process improvement model and management simulator for several manufacturing firms. Though each firm pursued a different program of improvement of one or more aspects of their system with varying degrees of success, the same model structure applies to each, lending support for applying the Navy S&T and eventually the more comprehensive Navy acquisition process as a fifth case study. This section of the research discusses how the SCIP model was used to demonstrate the merit of such a claim.

A simplified illustration of the production portion of the product development segment of the model is shown in Figure 5. The model consists of a section for Work In Process (WIP) with an initiation rate determined by several variables related to the quantity of resources devoted to WIP (shown as the circled elements in the upper right corner of the figure). The equations behind the model are included in an appendix to this report. Many of these variables are determined from

calculations during the simulation process. Others are user-defined characteristics representing policy decisions or system behavior.

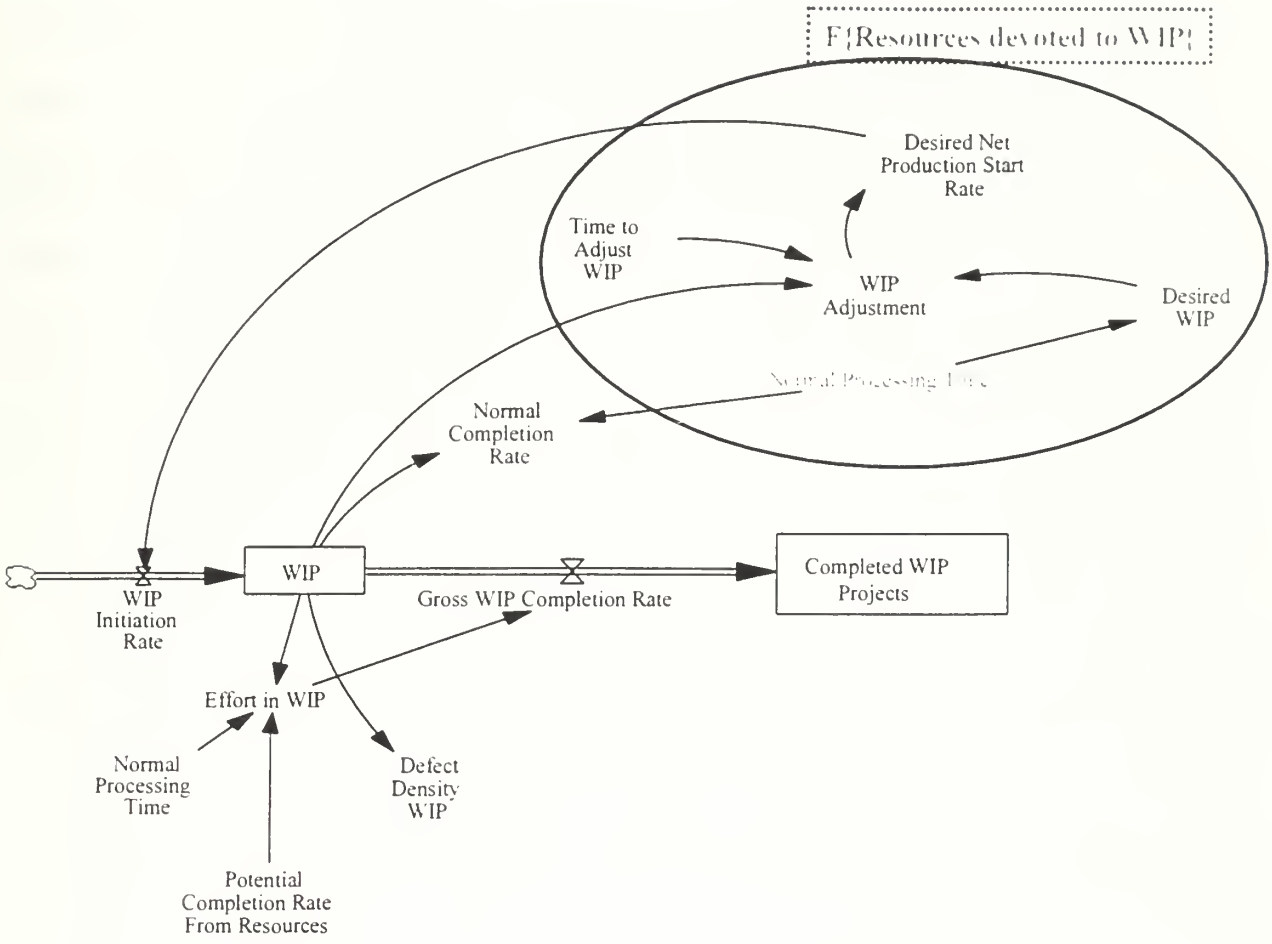

Figure 5: Simplified View of the WIP Section of the SCIP Model

The relationship to the Navy example is that WIP can be viewed as STIP. Instead of new products being developed for future use in the manufacturing system (i.e.,WIP), the STIP accounts for the chain of events of innovative new technological development that may eventually end up as new systems and components for the fleet. If a STIP project is successfully completed it progresses into a stock of completed STIP projects (shown as Completed WIP

Projects in Figure 5). This stock represents the S&T projects that are ready for further EMD. Recall that this logic precisely fits the discussion of Figure 4 in the previous section.

In addition to the factors that affect the WIP Initiation Rate (in Units/Day), also included in Figure 5 are other variables that determine system behavior. The Normal Processing Time (in Days) established the pace for processing the WIP into finished products. The throughput is tightly coupled to the completion rate (in Units/Day). The completion rate is determined by the amount of effort devoted to the existing WIP inventory. Effort in WIP is either the normal amount of time a WIP project would take to complete; or the amount of effort that is available based on existing resource constraints. This *either-or* approach ensures realism and limits the effort to the minimum of the available or desired completion rate. Another important element of Figure 5 is the Defect Density. This variable accounts for the inherent defects that exist in any real system. In WIP, a defect may be an out-of-tolerance part, a damaged component, etc. In the Navy S&T mindset, the defect is better represented as a "dead end" project. The logic is similar in that not all new projects involving innovation and advances in technology are successful in providing and end product.

A more detailed illustration of the product development portion of the SCIP model is shown in Figure 6. This figure begins to highlight the complexity that enters into the modeling process for real systems. Most notable are the three WIP stocks. This represents the various phases of WIP development as the most basic form (WIP 1) progresses through the development process towards the final stages of WIP (WIP 2 and WIP 3 in Figure 6). Also shown are the defects that either creep into the process or are undiscovered until late in the process. These defects

eventually cause rework or delays that result in the added use of resources. Defects reduce the Gross Completion Rate to arrive at a Net Completion rate. If the focus of the overall SCIP model was on the impact of the Net Completion of WIP, then the rightmost "cloud"[6] could then be expanded to cover additional behavior. Recall, however, that this stock and flow model is but a small part of the overall production process improvement model. As such, the original modelers found no need to continue to expand the production product development beyond that included in Figure 6. With the basic understanding of the existing SCIP model, attention now turns toward the applicability of using the same model structure for the Navy S&T process.

[6] A "cloud" is a system dynamics notation for representing additional behaviors or factors that are not specifically included in the formulation of the model.

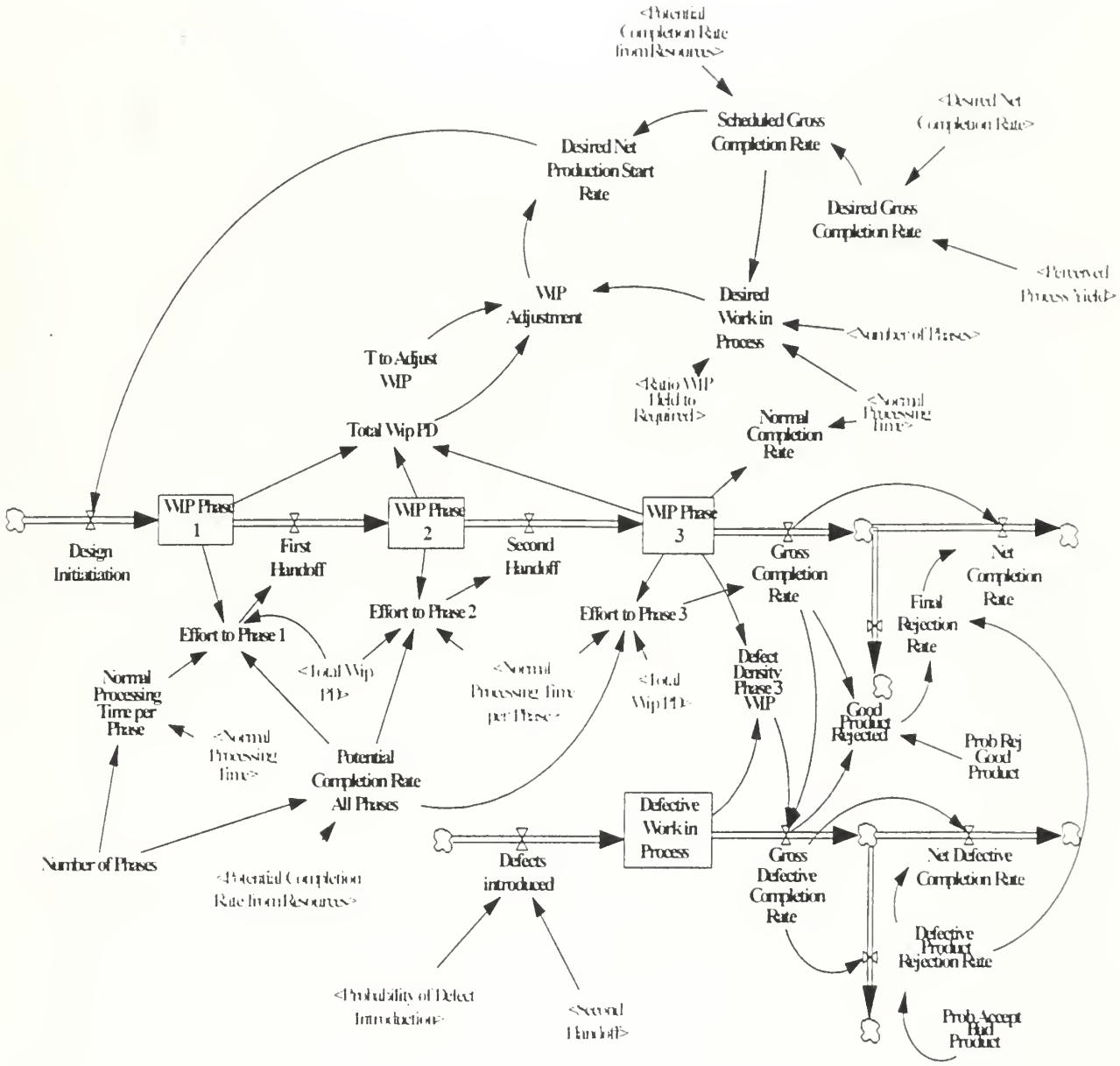

Figure 6: SCIP Model, Production Product Development Segment

3.3 SCIP Adjustments for Navy S&T

In Navy S&T terms, the product development model of Figures 5 and 6 requires modification to represent the S&T process. Some of the necessary adjustments are in name only and have been discussed as such—WIP becomes STIP and Days become Years, for example. Other minor alterations change the units of analysis as detailed in the appendices to this report. This further supports the claim that the SCIP model has potential application to an otherwise dissimilar system because it covers the new system's general behavior dynamic. The revised model, shown in Figure 7, represents the S&T version of the SCIP product development model. The documented model and equations are contained in Appendix A. The similarities in the fundamental structure and mathematical relationships remain intact. The differences merit discussion, however.

Since this feasibility analysis only investigates a portion of the SCIP model, many of the variables that would normally be calculated in other portions of the larger SCIP model must be specified externally for the S&T model. The variables in the upper right quadrant of Figure 7 are, as in the original SCIP model, representative of the resource allocation directed towards S&T projects. In the S&T model, the driving factor is funding devoted to S&T projects. Section 4 will present more information concerning the values used for the funding information as well as the other data analysis used in this research. The S&T process, like WIP, is broken into segments. The first, Phase 6.2 S&T, represents the applied research phase of technology development. A portion of the 6.2 research proceeds on to the next development stage, Phase 6.3 S&T, and may then continue towards EMD.

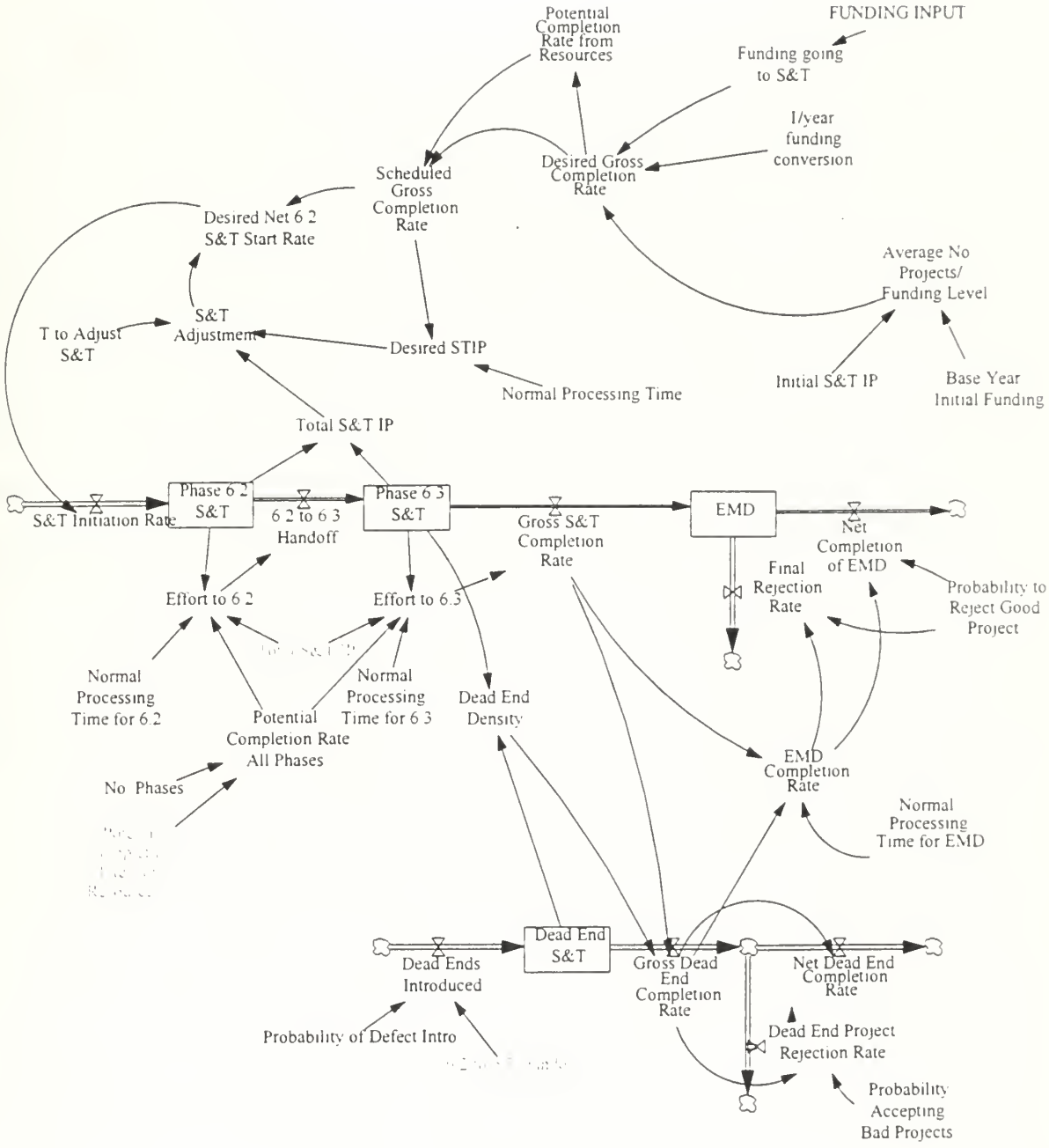

Figure 7: S&T Process Model

Recall from the earlier discussion that EMD projects represent those projects that have completed S&T exploration and concept development and are progressed to further stages of analysis and more detailed development. The likelihood of a project beginning in Phase 6.2 and progressing from unfocussed science into Phase 6.3 projects and ultimately EMD is small. The viability of EMD projects, like STIP, has some "dead end" rate associated with it, which decreases the actual number of useful projects for final introduction to the fleet. The S&T process model accounts for this system characteristic through higher probabilities for project rejection and defects than the SCIP model. The level of S&T project rejection is a significant influence on the performance of the S&T system. This aspect of the model will be addressed in the Simulation Analysis discussion that follows.

Despite the modifications to some variable names, units of measure, resource allocation method, and EMD stock, the original SCIP model remains substantially the same. The relationships that were found in four different industries seem to fit the general structure of the Navy S&T process. The quality of the fit can only be observed if quantified.

4.0 Simulation Analysis

4.1 Assumptions, Limitations, and Data Discussion

The S&T model presented in Figure 7 assumes that the S&T process is purely sequential and proceeds from Phase 6.2 to Phase 6.3 and potentially to EMD. This assumption was made to keep the model simple and consistent with the original SCIP model. In the majority of cases, this representation of the S&T process holds. There are cases, however, where new projects originate from external sources and can begin their S&T exploration anywhere along the stock and flow structure of Figure 7. Another major assumption was the exclusion of Phase 6.1 S&T. Before 6.2 applied research is a more general phase of "Basic Research"—Phase 6.1. This is the phase of S&T that is more broadly based and designed to explore new scientific discoveries or innovations without a clearly defined goal. Phase 6.1 research is sometimes referred to as strategic research and is conducted for future benefit without a predetermined application, as is the case for subsequent phases of S&T. The absence of Phase 6.1 in this model was done due to the lack of clearly defined project initiation and completion data and the link to a specific funding allocation. It is believed that such information would be available if additional S&T modeling were desired. For sake of this feasibility study, however, the 6.2—6.3—EMD flow is sufficient to capture the trends and behaviors. The historical actual funding levels for both 6.2 and 6.3 phases, as well as the current projections of funding, were collected (Figures 8 and 9) and used in the S&T model.

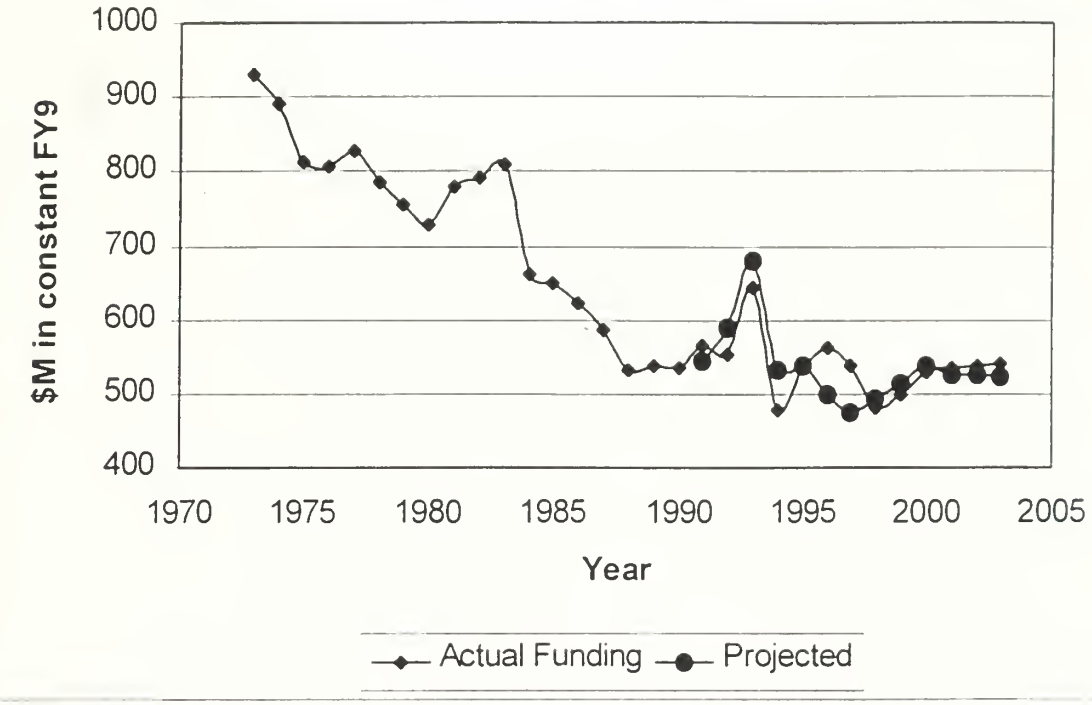

Figure 8: Phase 6.2 (Applied Research) S&T Funding

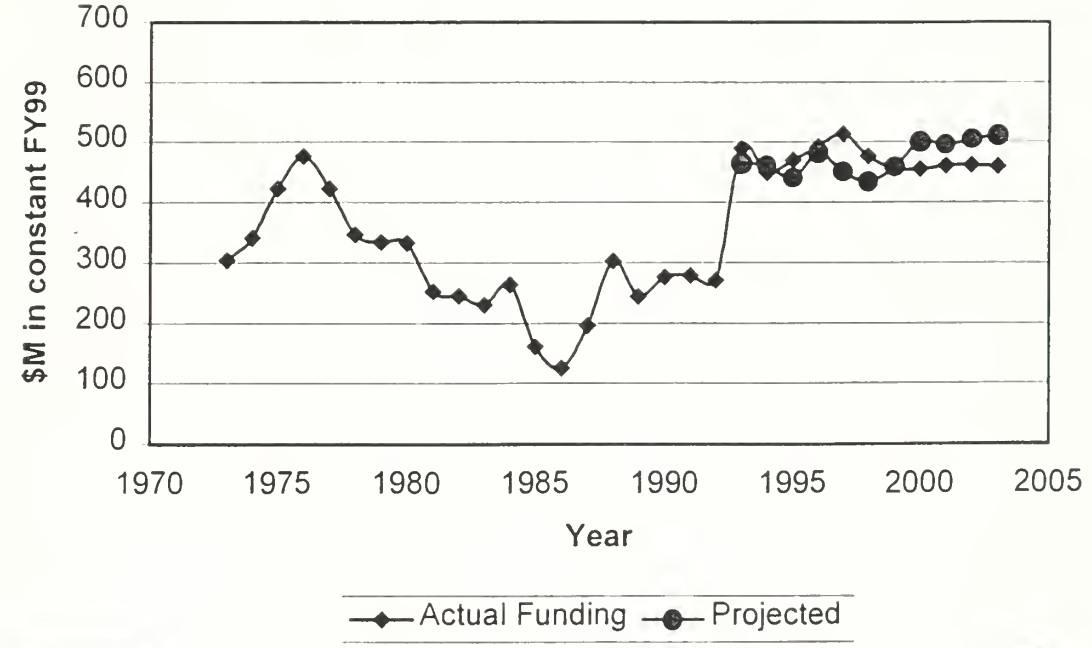

Figure 9: Phase 6.3 (Focused Research) S&T Funding

Since the original SCIP model had only one source for resources to initiate WIP, the S&T model is treated the same way. To accomplish this, the individual 6.2 and 6.3 funding projections were added together, Figure 10. An interesting observation in Figure 10 is highlighted by the linear regression line through the data. It shows a nearly constant combined total S&T funding projection into the near future.

The aggregate funding simplification will erroneously inflate the total number of Phase 6.2 S&T since more resources are flowed through the 6.2 process before reaching 6.3. In addition, since there is no attrition in the base model between 6.2 and 6.3, the inflated 6.2 S&T stock will further inflate Phase 6.3 S&T and eventually EMD to even higher levels. This behavior is a consequence of the SCIP model treatment of WIP, but is tolerated during the first review of the applicability of the SCIP structure to the Navy process.

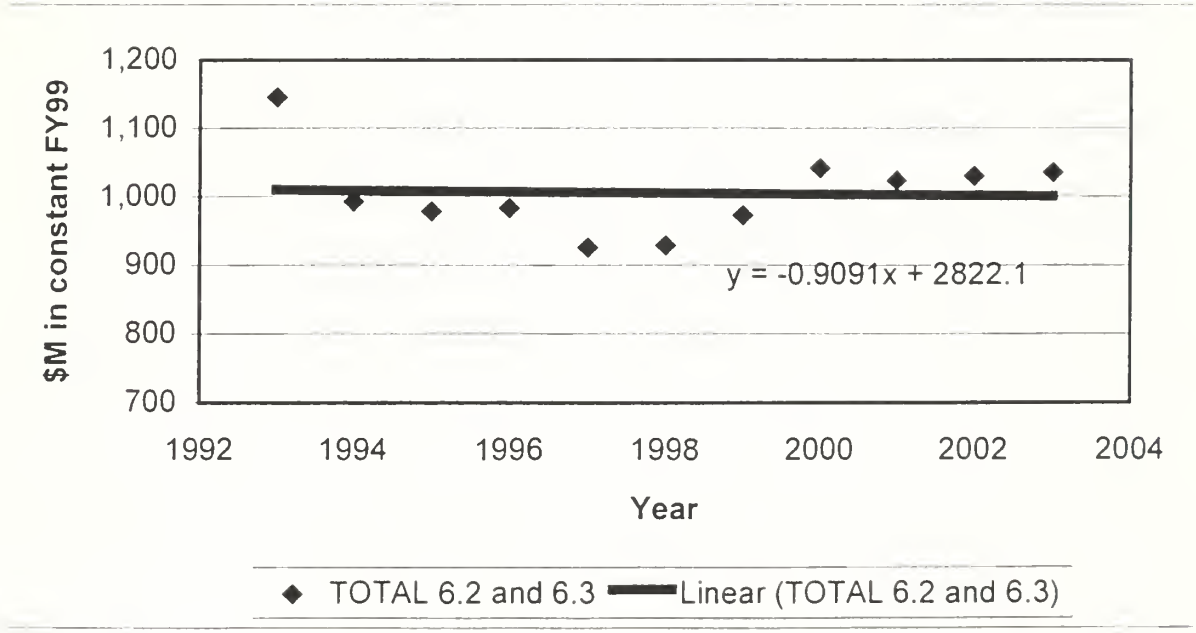

Figure 10: Combined S&T Funding Projection

Another data collection requirement traced the initiation and completion rates for the S&T process. This information helped to establish the initial values for the stocks and the average completion times for the S&T phases. The information consisted of actual data on funding trends, funding duration and magnitudes, and number of new projects initiated in a sample year. Several simulation runs were made with the established structure to determine if the model produced reasonable results. The numerical values presented here are generalized and not intended to quantify the exact system behavior.[7] This method was arguably imprecise, but nonetheless provided behavioral insights within the model. Due to the simplified model to which the data was applied, additional precision in the initialization data would not sufficiently add to the analysis presented here. This is an obvious area for more in-depth investigation before enacting policy changes based upon the output of the simulation. A sample of this output is now presented.

4.2 Simulation Results

Once some reasonable data was assembled and the S&T process understood, the revised SCIP production product development model was initialized for simulation. The first step in this process was to convert the funding variables (in units of Dollars/Year) into consistent units for application to the SCIP model structure—Units/Period. The proper units for S&T project initiation are "Projects/Year." By approximating a typical number of 6.2 projects and the experience that there are generally only 10% as many 6.3 projects compared to 6.2 efforts, a

[7] This data presentation method assisted in data collection by removing the hesitation to releasing information that, though unclassified, may be viewed as sensitive in some circles.

units conversion factor was used—Average No. Projects/Funding Level—to translate the 1998 funding levels (in Dollars) into the proper initiation rate—Projects/Year. The interviewing and discovery process also highlighted the same 1:10 ratio as a good approximation for the order of magnitude cost increase observed for 6.3 projects. This estimate was supported by additional quantitative data that estimated 6.3 projects as costing eight times that of corresponding 6.2 projects.

The simulation analyses that follow are intended to illustrate the S&T system behavior in response to various changes in process parameters. Specifically, the changes in 1) funding levels relative to the projected levels (Figure 10); 2) processing time for S&T; and 3) defect introduction factors will be presented. The resulting analyses are intended to highlight the leverage areas within the simplified model for altering the S&T system. All simulations assume a shock to the system at time equal to one year. The shocks are made large enough to magnify the effect for easier illustration. All simulations begin from the initial conditions and constants documented in Appendix A.

In the first illustration, the single variable altered was "Funding Going to S&T" which was simulated as a step change in funding beginning at year 1 and remaining constant thereafter (see Figure 11). In the actual Navy S&T system, some noise and other factors—politics, world threat levels, etc.—would invariably cause oscillations in the step functions presented.

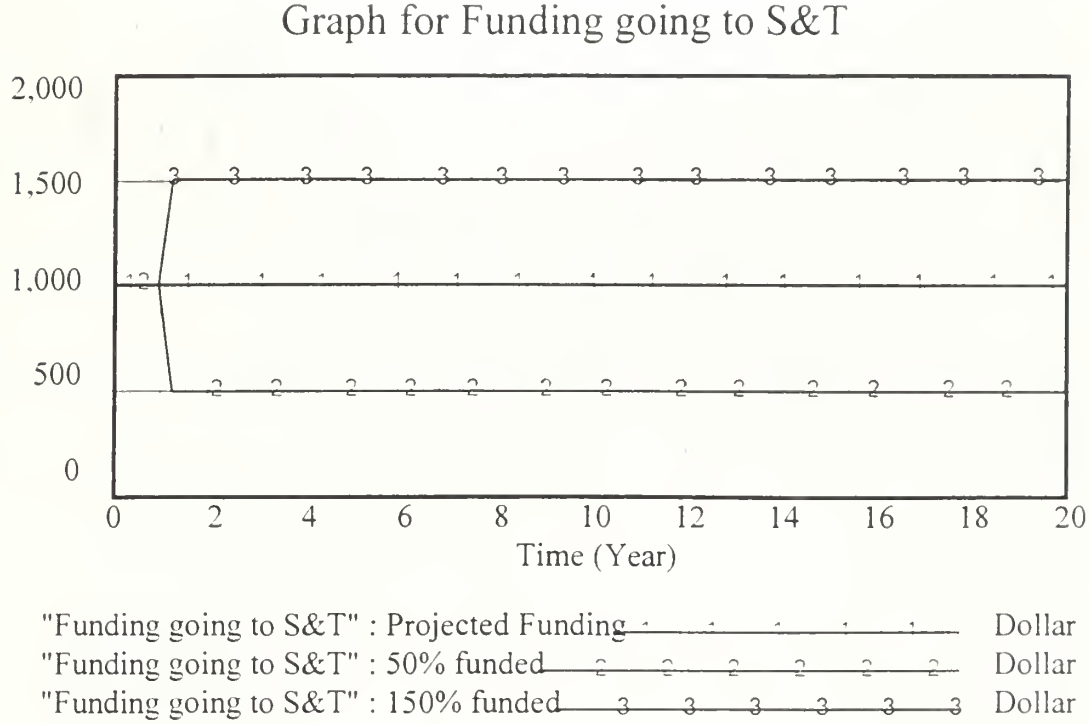

Figure 11: Simulation S&T Funding Inputs
(Vertical axis is base year funding levels in Dollars)[8]

The resulting S&T Initiation Rate for these funding inputs shows that the system responds rapidly with new project starts. The time constants selected for the S&T system end up clearing the increased funding motivation to conduct more S&T and the initiation rates decay within 3 years, see Figure 12. This behavior stems from the structure of the model, which attempts to clear a backlog of STIP just as WIP throughput was desired from the SCIP model. The initial value for S&T initiation represents an equilibrium level of introductions based upon ongoing efforts (trace 1) before a step change—traces 2 and 3. Note that in the second scenario, funding is cut to the point where no new projects are initiated as determined by the S&T Adjustment and the Scheduled Gross Completion Rate, Figure 7 and appendix A. This is a very dramatic system behavior in that it shows how a significant and sustained cut to S&T funding can generate such a

large gap between desired S&T and that which is possible (i.e., limited due to lack of funds) that the system of Navy S&T is effectively shut down for a decade. Notice in trace 2 of Figure 12, that new S&T begins again in year 13. In the real world, this represents an unbearable burden on the existing infrastructure of the S&T system and there is little chance that the system would remain idle for so long. It would more realistically be dismantled and extremely costly to reconstitute should a new need be identified downstream. These unexpected insights from system behavior are useful to Navy decision makers.

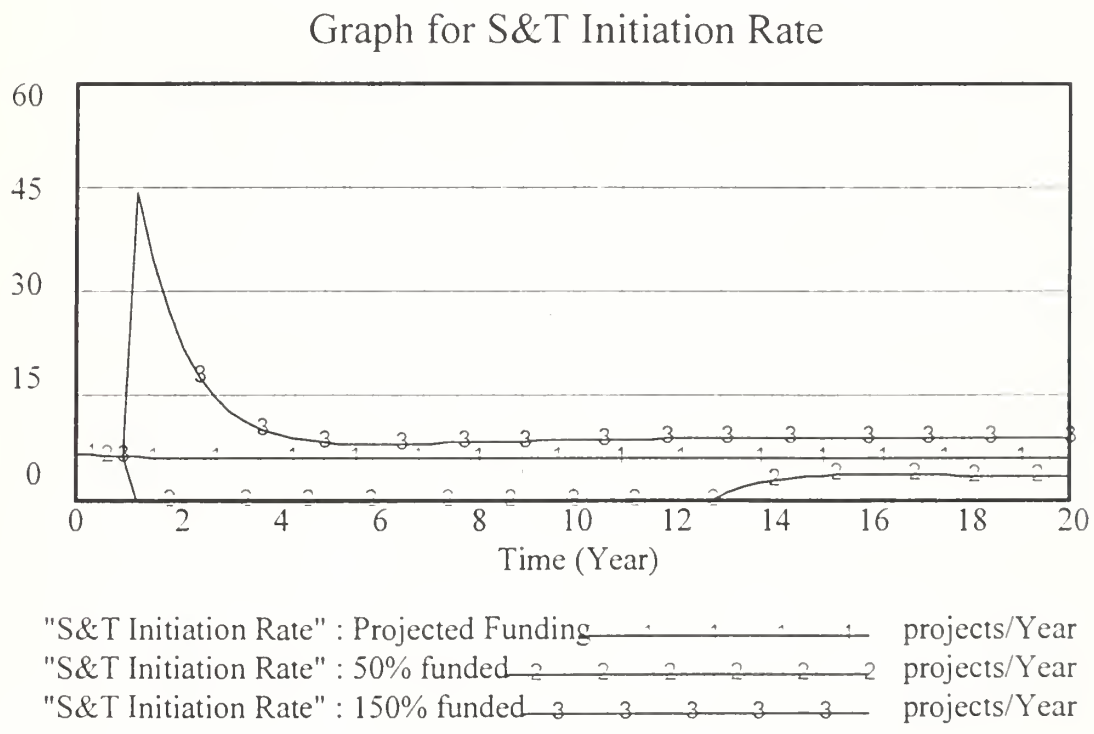

Figure 12: S&T Initiation Rate
(Vertical axis is number of Projects/Year)

[8] The funding values presented are representative of the actual values but are not the real dollar values.

The resulting EMD Completion Rate, an important variable that determines the rate at which projects could potentially be turned over from the scientific community to the Navy fleet, is shown in Figure 13. This figure shows the expected value of three projects per year in equilibrium at the projected funding levels of Figure 10 (trace 1). Since there are delays in initiation, Phase 6.2 and Phase 6.3, the response to a shock is delayed for EMD completion. Raising or reducing funding levels results in a higher and lower equilibrium values, respectively, as would be expected.

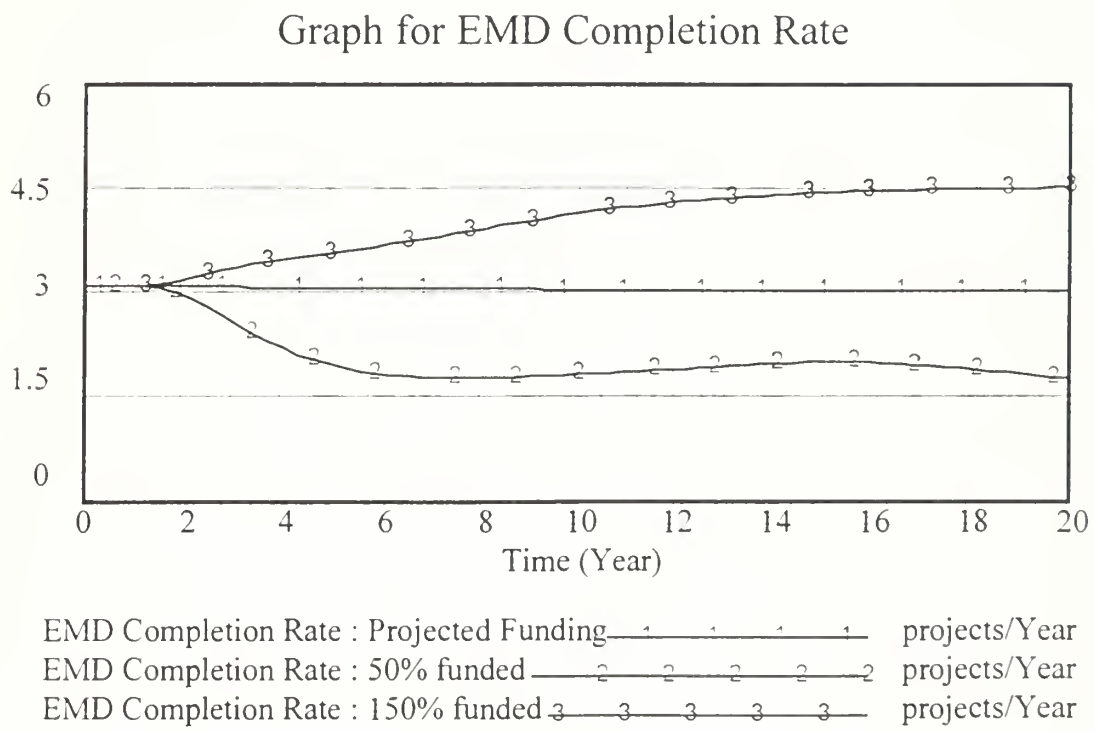

Figure 13: EMD Completion Rate—Response to Changes in Funding Levels
(Vertical axis is number of Projects/Year)

The second system shock considered is the time delay involved in the processing time necessary for S&T projects. The EMD processing time is altered from the base case of 3 years in the 50% of projected funding case (trace 1). Results for EMD processing time of 1.5 years and 4.5 years (traces 2 and 3, respectively) illustrate system response, see Figure 14. The shorter processing time causes the system to reach its final equilibrium sooner[9], but also exhibits more overshoot. The longer EMD processing time scenarios presents the opposite effect. Similar results would follow when all processing times for 6.2, 6.3 and EMD are reduced, but since the EMD is the last delay, it dominates the behavior. If a decision maker wanted more EMD projects available to the fleet, then the policy of merely speeding up processing has limited capacity to change the overall system response.

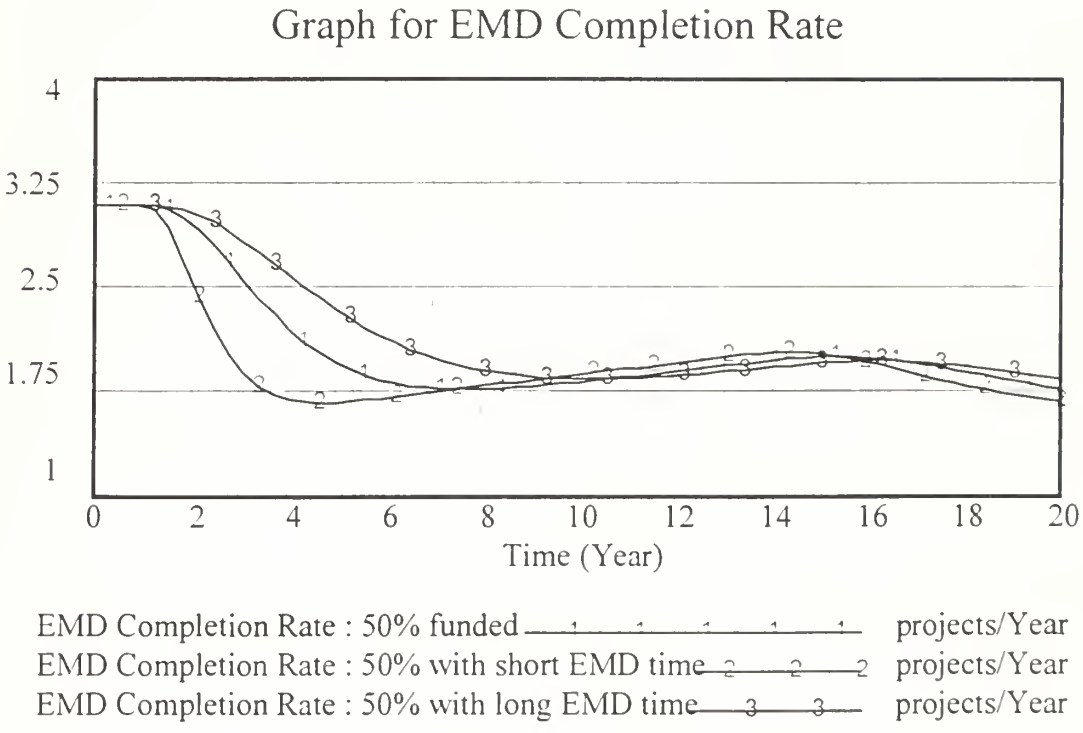

Figure 14: EMD Completion Rate—Response to Changing EMD Processing Time
(Vertical axis is number of Projects/Year)

[9] The term "equilibrium" is used loosely here in that there is still some oscillation present. This keeps the time axis consistent across all discussions.

Another method of increasing the EMD completion Rate may be to reduce the dead ends experienced in the S&T process. This scenario is presented in Figure 15 for different values of the Probability of Defect Introduction. The base case assumes one half of the EMD projects that are possible actually come to fruition. In other words, although a project may have completed Phases 6.2 and 6.3, there is a 50% chance that it would not succeed through the completion of the EMD process. The second analysis reduces the defects by 50% and shows a higher level of projects availability.

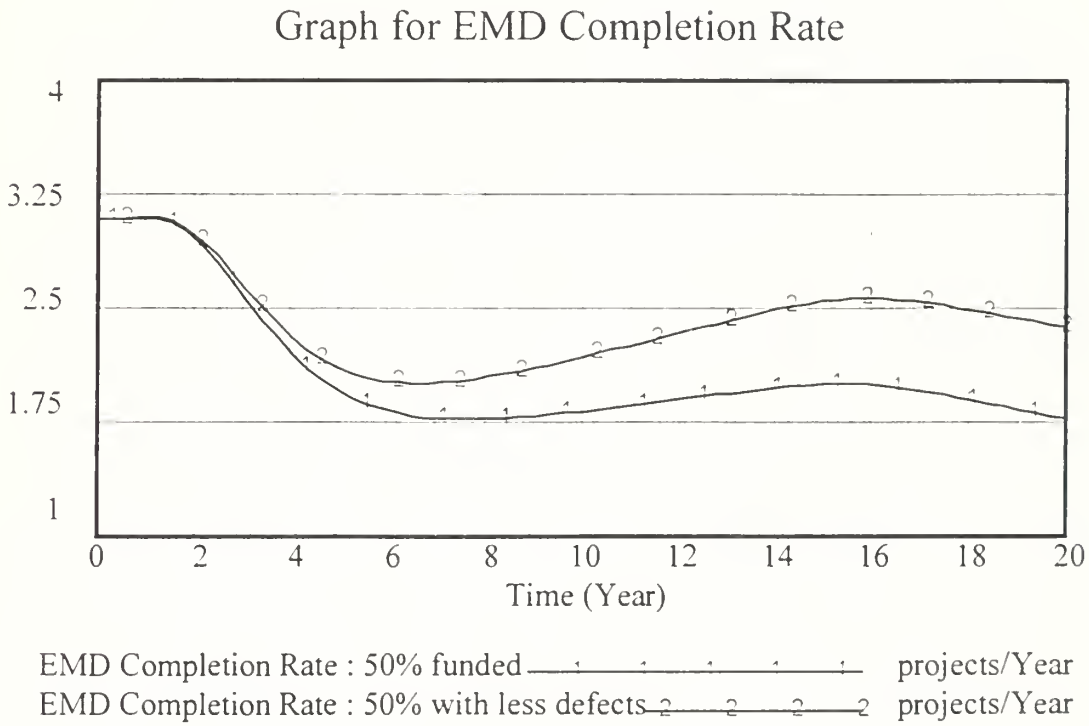

Figure 15: EMD Completion Rate—Response to Defect Introduction
(Vertical axis is number of Projects/Year)

Comparison of the previous two policy levers indicates that the defect reduction policy appears to provide a greater EMD completion rate compared to the reduced cycle time policy. As shown in Figure 16, the reduced defects trace generates more EMD completions and a higher equilibrium value. This suggests that the defect reduction policy is the dominant lever for process improvement initiatives within the formulated S&T system. This observation is made in the absence of the real world issues involved in actually accomplishing a 50% reduction in either the processing time or the defect introduction rate. Both process improvement efforts are extreme examples, but more realistic improvement programs could be investigated using a more refined S&T model.

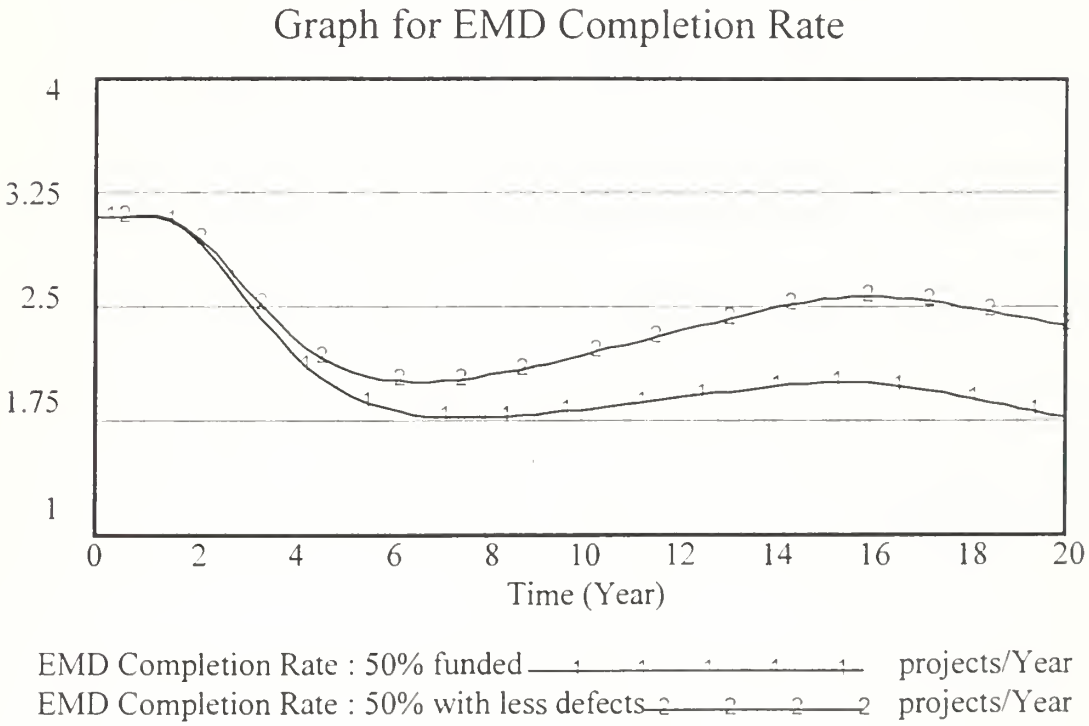

Figure 16: Defect Reduction versus Processing Time Reduction
(Vertical axis is number of Projects/Year)

The reader is strongly cautioned against interpreting the results of Figures 11-16 as forecasts or policy recommendations. The observed trends, at the feasibility overview perspective, are consistent with the actual S&T process and were obtained without requiring many alterations to the existing SCIP model. The model illustrates behavioral trends not optimal policy parameters. These trends allow decision makers to experiment with their policy decisions before committing to an improvement policy that may not be most effective in satisfying the desired goal. This result is the most powerful benefit of this effort and the focus of the remarks that follow.

5.0 Conclusion and Remarks

5.1 Insights

As all system dynamics practitioners are aware, all models are wrong, but some models are useful. I believe that this adaptation of the SCIP model, though providing only a rough fit to the actual Navy S&T process, is useful. That use is not fully realized in the current form, but rather in the potential that has been identified for using other elements of the existing SCIP model. The current SCIP model is a detailed analytical tool that provides an excellent training and decision tool for helping managers expand and better understand their existing mental models. With the expanded systems view of their environment, they can make more informed policy decisions and recognize the high leverage variables for implementing the desired short and long-term policy results for sustained process improvement.

A major issue that was discovered as part of this research was the difficulty in finding a reasonable "fit" between an existing model and an existing process. This was a difficult task that went through several iterations before finding an area that seems to have worked. I would caution future efforts against forcing such a fit in other models or in additional areas of the SCIP model.

The fit between product development and S&T evolved through interviews and understanding of both process and model structure. Dominance in either one of these areas only complicated the process and had to be balanced. The approach was iterative out of necessity and it was difficult to stay within the same structure as the existing model. Often it was initially easier to add new structure only to realize that such shortcuts reduced the objective of determining the feasibility of

adding a new case to the current SCIP model. In the end, only minor modifications were necessary for making the general behavior of the Navy's S&T process fit that of industry's experience.

5.2 Follow-on Efforts and Final Remarks

Additional data collection is necessary if a detailed simulation is desired. The data collected for the present research permitted analysis of feasibility and behavioral trends only. Much of the information obtained from interviews and correlation between multiple pieces of the S&T puzzle was subjective in nature and not useful beyond observing overall trends in the model's behavior. Another significant part of the S&T process—Phase 6.1, basic research—should be included in the expanded data collection effort and would add considerably to policy decision making.

The S&T process simulation exhibits many of the expected trends, but lacks precise behavioral descriptions in all situations. The major reason for this shortcoming was the single S&T project initiation source upstream of Phase 6.2 S&T. The next iteration of the model could, while keeping the same general structure as that already presented, break the 6.2 and 6.3 processes into separate flows that originate from projected funding resources for each area. One recommendation would show the Phase 6.3 S&T stock stemming from two inflows—the specific funding directly allocated for 6.3 projects and that portion of 6.2 projects that have been marked for further exploration as 6.3 efforts. Each flow would have separate initiation and completion success rates that would come together in determining the EMD stock and flow process.

The benefits of the SCIP model are in helping managers understand more of the feedback effects that they would have otherwise neglected. These benefits are quite powerful and significant. When the system dynamics discipline is applied to understanding process improvement initiatives and outcomes, there is a great deal for decision makers to learn.

Applying new cases and industries to the existing model seems to be reasonable but requires substantially more data collection and "fine tuning" than the methods presented here. Finally, returning to the initial question "Can the U.S. Navy Acquisition Community Learn from Industry Behavior?"—I believe it can. The Navy can use a proven industry model to understand industry practices at the same time it populates the model with the specific differences it faces within the DoD environment. The learning from such an effort is potentially useful because it expands the current scope of Navy decision makers mental perception of their system and the many hidden feedback effects. The system dynamics method and Simulation for Continuous Improvement Process model can act as a bridge between where the Navy acquisition process is and where it may be able to reach. If the Navy leaders can cross the bridge and understand the impact of their policy decisions then the results could provide sweeping returns to our Navy and our country.

Appendix A: S&T Model Documentation

```
********************************************************
        .COMMENTS
********************************************************
                This model is developed from the original Continuous Process Improvement
                Learning Laboratory (CIPLL) V1.0 August 1998.
                Uses VENSIM DSS32 Version 3.0B
                Modifications are made to fit the differences observed for the Navy S&T process,
                but these changes are kept to a minimum.
                William J. Brougham, MIT Sloan School, MOT Program Thesis, 1999.
                Contact the author with questions.


"1/year funding conversion"=
        1
        ~       1/Year
        ~       A conversion variable to convert funding levels (collected as a Dollar \
                value) to annualized funding (in Dollar/Year).
        |

Net Completion of EMD=
        EMD Completion Rate*(1-Probability to Reject Good Project)
        ~       projects/Year
~       The opposite of the Final Rejection Rate, this accounts for the portion of \
                EMD projects that actually become completed projects and could then be \
                passed to another portion of the S&T community or the Navy for use.  This \
                value is not calibrated for the model at this time and works with the \
                Final Rejection Rate.
        |

Final Rejection Rate=
        EMD Completion Rate*Probability to Reject Good Project
        ~       projects/Year
        ~       Accounts for the portion of EMD projects that are rejected, for whatever \
                reason--dead end, lack of interest, lack of need, etc.  As with the Net \
                Completion of EMD, the split between rejection and completion is not \
                calibrated at this time and not used in the discussion.
        |

EMD Completion Rate=
        DELAY3(("Gross S&T Completion Rate"-Gross Dead End Completion Rate),Normal
Processing Time for EMD\
                )
        ~       projects/Year
```

~ A third order delay of the Gross Completion Rate less the Gross Dead End \
Completion Rate. Based upon the normal time it takes an EMD project to be \
completed.
|

"6.2 to 6.3 Handoff"=
"Effort to 6.2"
~ projects/Year
~ The completion rate of 6.2 and hence initiation of 6.3. Assumes no other \
means to begin a 6.3 or EMD project. This is a simplification but covers \
the vast majority of projects.
|

Normal Processing Time=
3
~ Year
~ Minimum time to process because of logistical constraints. This variable \
is a carry over from the CIPLL/SCIP model but is still useful. In this \
model there are individual 6.2, 6.3 and EMD "Normal Completion Times" but \
they are all the same.
|

"Average No. Projects/Funding Level"=
"Initial S&T IP"/Base Year Initial Funding
~ projects/Dollar
~ A constant number for the costs of a typical projects. Note that the \
number of 6.2 projects is more likely to fluctuate because they are \
smaller scale compared to 6.3. In general, the funding level for each \
project type is the same because if something is very complex it is nearly \
always broken into smaller project pieces in the S&T 6.2 and some 6.3 \
phases.
|

Base Year Initial Funding=
916
~ Dollar
~ FY98 actual 6.2 and 6.3 S&T project funding
|

Scheduled Gross Completion Rate=
min(Desired Gross Completion Rate,Potential Completion Rate from Resources)
~ projects/Year
~ Prevents the EMD projects from starting at a faster rate than STIP could \
be completed.
|

Normal Processing Time for EMD=
3
~ Year
~ Time to complete a typical EMD project. Generally part of a three year \
contract to demonstrate a technology or group of technologies.
|

Desired STIP=
Scheduled Gross Completion Rate*Normal Processing Time
~ projects
~ The desired amount of STIP as determined by the Desired Gross Completion \
Rate and the Normal Processing Time for completing the projects. This \
forces the Potential and Desired to be the same since, unlike the \
CIPLL/SCIP model, no ratio of the actual compared to required is used.
|

FUNDING INPUT=
0
~ Dollar
~ An input for simulation runs of funding scenarios. Could be linked to \
other resource consumption as a portion of the total Navy budget. This \
parameter is adjusted depending on the run in question as a multiplier to \
the constant funding level from the collected data. It would need to be \
adjusted is new data suggested a funding level for 6.2 and 6.3 other than \
that used in this version.
|

Desired Gross Completion Rate=
"Funding going to S&T"*"Average No. Projects/Funding Level"*"1/year funding conversion"
~ projects/Year
~ The desired number of projects to be completed which is the driver for \
what needs to be started.
|

"Desired Net 6.2 S&T Start Rate"=
max(0,Scheduled Gross Completion Rate+"S&T Adjustment")
~ projects/Year
~ The desired number of projects flowing into 6.2 STIP as determined by the \
desired completion rate and the adjustment for any shortfalls in STIP.
|

"Funding going to S&T"=
1005.7*(1+FUNDING INPUT*STEP(1,1))
~ Dollar
~ The "resources" going to initiate S&T. This is based on the funding \

```
        allocated to S&T projects for a 1998 base year 6.2 and 6.3 using the \
        approximate linear regression for the combined S&T budget contained in the \
        body of the thesis.  Assumes a constant level initially then steps the \
        funding in year 1 based on the value of the Funding Input Multiplier.  \
        Could also be changed to match other funding trends if desired.
    |

"S&T Initiation Rate"=
    "Desired Net 6.2 S&T Start Rate"
    ~   projects/Year
    ~   The S&T effort initiated from new funding or sustained from existing \
        funding.  Note that this single initiation pint for the entire S&T system \
        is an oversimplification for the model that is a carry over from the \
        CIPLL/SCIP model.  This area needs to be changed in future S&T modeling \
        efforts.
    |

"T to Adjust S&T"=
    1
    ~   Year
    ~   The time it takes to adjust the STIP to desired levels.  This is really \
        based on an annual review process not a real time optimization approach.  \
        Since projects are approved annually, the 1 year adjustment value is a \
        very reasonable estimate.
    |

Potential Completion Rate from Resources=
    Desired Gross Completion Rate
    ~   projects/Year
    ~   The potential for completion for all phases of S&T.  Maintained to keep \
        CIPLL/SCIP structure, but not used here.  Set equal to Desired for \
        simplification due to lack of logistical limitation data.
    |

"S&T Adjustment"=
    (Desired STIP-"Total S&T IP")/"T to Adjust S&T"
    ~   projects/Year
    ~   The Navy seeks to adjust the STIP to desired levels over a time to adjust \
        S&T to the desired level.
    |

Normal Processing Time 0=
    3
    ~   Year
    ~   Minimum time to process because of logistical constraints
    |
```

```
Dead End Density=
        min(1,zidz("Dead End S&T","Phase 6.3 S&T"))
        ~       Dimensionless
        ~       Represents the fraction of 6.3 S&T projects which are "defective".  This \
                means that in the end, they will not lead to a viable system along its \
                current path.  Capped to be 100% of the existing 6.3 projects for the \
                first pass through the model.
        |

Dead End Project Rejection Rate=
        Gross Dead End Completion Rate*(1-Probability Accepting Bad Projects)
        ~       projects/Year
        ~       The number of defective projects, even though they were completed, that \
                are dead ends AND actually got discovered and rejected.
        |

"Dead End S&T"= INTEG (
        Dead Ends Introduced-Gross Dead End Completion Rate,
                "Initial S&T IP")
        ~       projects
        ~       The stock of defective S&T projects in process.  The inflow is the number \
                of defective projects into the S&T process flow and the outflow is the \
                Gross Dead End Completion Rate (the gross number of dead end projects \
                that, for some reason, ended up getting completed).  Initial value is a \
                distribution of the initial number of projects in the system distributed \
                over the number of S&T phases, as it is in the SCIP/CIPLL model.
        |

Dead Ends Introduced=
        "6.2 to 6.3 Handoff"*Probability of Defect Intro
        ~       projects/Year
        ~       The rate of introducing bad projects unknowingly into the EMD stock.  \
                Usually low but could become a significant expense if the volumes of S&T \
                projects is very large.  "bad" is nomenclature carried over from \
                SCIP/CIPLL model and only suggests that some projects don't make it--they \
                are hence bad.
        |

"Effort to 6.2"=
        min("Phase 6.2 S&T"/"Normal Processing Time for 6.2",(Potential Completion Rate All
Phases\
                *"Phase 6.2 S&T"/"Total S&T IP"))
        ~       projects/Year
        ~       The lesser of the normal minimum time to push a phase of S&T through to \
                the next stock AND the amount of available completion capacity from \
```

```
        resources.
    |

"Effort to 6.3"=
    min("Phase 6.3 S&T"/"Normal Processing Time for 6.3",(Potential Completion Rate All
Phases\
        *"Phase 6.3 S&T"/"Total S&T IP"))
    ~   projects/Year
    ~   The lesser of the normal minimum time to push a phase of S&T through to \
        the next stock AND the amount of available completion capacity from \
        resources.
    |

EMD= INTEG (
    "Gross S&T Completion Rate"-Final Rejection Rate-Net Completion of EMD,
        9)
    ~   projects
    ~   This is the stock of completed 6.2 and 6.3 S&T that represents the state \
        of projects which undergo more detailed scrutiny in the operational \
        setting vice laboratory.  Still not ready for the fleet, however.  Initial \
        value based on approximately 3 new projects completed and begun each year \
        and a 3 year processing time.
    |

Gross Dead End Completion Rate=
    "Gross S&T Completion Rate"*Dead End Density
    ~   projects/Year
    ~   The number of projects completed multiplied by the fraction of Phase 6.3 \
        projects which are dead ends but not yet known to be so.
    |

"Gross S&T Completion Rate"=
    "Effort to 6.3"
    ~   projects/Year
    ~   Completion of the S&T phase and transition rate to EMD projects.
    |

"Initial S&T IP"=
    22
    ~   projects
    ~   Starting number of S&T initiatives when system model begins.  Comprised of \
        approximately 60 6.2 projects with an avg. cycle time of 3 yrs=20/yr new \
        project/yrs and 1/10 as many 6.3.  Value from data and interviews.
    |

Net Dead End Completion Rate=
```

Gross Dead End Completion Rate-Dead End Project Rejection Rate
~
~ The number of defective projects discovered prior to commitment to putting \
them into the fleet development stock.
|

"No. Phases"=
2
~ Dimensionless
~ Number of S&T phases involved in model from inception to EMD. Ignores 6.1 \
as a first approximation of the system.
|

"Normal Processing Time for 6.2"=
3
~ Year
~ Set at 3 yrs as a normal value based on the funding profile generally used \
by ONR. SCIP/CIPLL model is more complex due to logistic limitations.
|

"Normal Processing Time for 6.3"=
3
~ Year
~ Set at 3 yrs as a normal value based on the funding profile generally used \
by ONR. SCIP/CIPLL model is more complex due to logistic limitations.
|

"Phase 6.2 S&T"= INTEG (
"S&T Initiation Rate"-"6.2 to 6.3 Handoff",
45)
~ projects
~ The stock of 6.2 S&T projects. Initialized based on the system behavior \
in equilibrium as well as expert interviews.
|

"Phase 6.3 S&T"= INTEG (
("6.2 to 6.3 Handoff"-"Gross S&T Completion Rate"),
45)
~ projects
~ The stock of 6.3 S&T projects. Initialized from interviews, data and \
system behavior in equilibrium. Note that the value is inflated from what \
would actually be the case if 6.3 efforts were not solely dependent on the \
completion of 6.2. The value of the stock is useful only for behavior \
trends, not actual understanding of the number of 6.3 projects.
|

Potential Completion Rate All Phases=

Potential Completion Rate from Resources/"No. Phases"

~ projects/Year

~ The resource capacity that could be devoted to "effort" for a phase of \
S&T. If all resources where poured into completing vice originating new \
projects, it would be reflected here.

|

Probability Accepting Bad Projects=

0.05

~ Dimensionless

~ Probability of not catching a dead end project before it progresses into \
the fleet. In other words, the S&T testing and development doesn't catch \
the flaw. Should be a low number but non-zero.

|

Probability of Defect Intro=

0.5

~ Dimensionless

~ Value which is carried over from the CIPLL model. Injects some amount of \
error into projects in the EMD phase. In other words, they made it \
through the 6.2 and 6.3 phases "error free". (Note: This is not the \
observed yield out of 6.3. This will be higher since the yield out of \
Total S&T IP is also decreased by other dead ends..

|

Probability to Reject Good Project=

0.33

~ Dimensionless

~ Probability of rejecting or terminating an otherwise good EMD project. \
Accounts for such reasons as a dead end (which would be quite low by the \
time a project reaches the EMD stage of development), lack of interest \
(meaning the Navy demand for the system is not "pulling" the development), \
lack of funding (a good project among many good projects that simply \
cannot be continued due to budget limitations), etc. Not a calibrated \
value at this time, but that does not come into the discussion of the \
system behavior.

|

"Total S&T IP"=

"Phase 6.2 S&T"+"Phase 6.3 S&T"

~ projects

~ Total number of ongoing S&T projects in the 6.2 and 6.3 phases. Further \
efforts would include phase 6.1.

|

```
TIME STEP  = 0.015625
        ~       Year
        ~       The time step for the simulation.

                ********************************************************
                .Control
                ********************************************************
        |

FINAL TIME  = 20
        ~       Year
        ~       The final time for the simulation.
        |

INITIAL TIME  = 0
        ~       Year
        ~       The initial time for the simulation.
        |

SAVEPER=
        TIME STEP * 20
        ~       Year
        ~       The frequency with which output is stored.
        |
```

Appendix B: CIPLL Model Documentation

[Repenning, *et al.* 1998]

CIPLL equations and documentation (partial for "Production PD" and supporting sections only)
****

.WIP
**********~

The work in process flow group determines the net completion rate or the shipment rate. The net completion rate is the gross completion rate less the final rejection rate. The gross completion rate is determined by the level of work in process and the normal processing time. The normal processing time is an improvable parameter. Furthermore, the gross completion rate is constrained by labor and capital resources. The group includes a defective work in process co-flow; this flow is made up of defects present when the raw materials entered the process as well as defects introduced during the completion process. Defective product can be discovered during testing based upon the probability of rejecting bad product. Also, good product can be found defective based on the probability of rejecting good product. The desired level of work in process is determined by the desired gross completion rate. The desired gross completion rate in turn is determined by the desired net completion rate and the effective process yield. The desired net completion rate is determined by the order backlog and the delivery delay. The expected process yield based upon a perception of historical process yields.

Desired Gross Completion Rate=
max(0,min(Desired Net Completion Rate,2 * Suggested Net Completion Rate) / Perceived Process Yield)
~ Units/Day
~ The desired number of units completed is the net number of units completed adjusted by the expected process yield.
|

Process Yield=
xidz(Net Completion Rate,Gross Completion Rate,Perceived Process Yield)
~ Dimensionless
~ The process yield is the ratio of the number of net units shipped/completed to the total completed. However, if there are no units being completed the perception of process yield retains its prior value.
|

Expected Rework=
Final Rejection Rate 2 * Fraction Reworked
~ Units/Day
~ |

Defective Rework=
Rework * Defect Density WIP

~ Units/Day
~ |

Defective Work in Process=
INTEG (Defective Material into Process + Defects introduced - Gross Defective Completion Rate + Defective Rework, Initial Def WIP)
~ Units
~ The stock of defective units in process. The inflow is the number of defective materials into process and the outflow is the gross number of defective units completed.
|

Work in Process=
INTEG (Net Prod Start Rate + Rework - Gross Completion Rate, Initial WIP)
~ Units
~ Number of units in process waiting to be completed. Initially, is equal to the desired level of work in process. The change is determined by the net material start rate less the gross completion rate in a given time period.
|

Fraction of work redone=
0.2
~ Dimensionless
~ The fraction of work that must be redone in order to rework a rejected product.
|

Fraction Rework in WIP=
Rejects / Work in Process
~ Dimensionless
~ |

Net Completion Rate=
Gross Completion Rate-Final Rejection Rate 2
~ Units/Day
~ The number of units shipped is equal to the total finishing rate less the \
final scrap rate.
|

Good Product Rejected=
(Gross Completion Rate-Gross Defective Completion Rate)*Prob Rej Good Product
~ Units/Day
~ The amount of good product rejected is the number good products completed multiplied by the probability of rejecting a good unit. The number of good units completed is the number of total units completed less the number of defective units completed.
|

Normal Completion Rate=

Work in Process/(Normal Processing Time * (1 - Fraction Rework in WIP) + Fraction Rework in WIP * Normal Processing Time * Fraction of work redone)
~ Units/Day
~ The normal completion rate is determined by the available units to be completed and the normal processing time.
|

Rejects=
INTEG (Final Rejection Rate 2 - Scrapping - Fixing, Initial WIP * Fraction Reworked * Initial Expected Process Yield)
~ Units
~ |

Final Rejection Rate 2=
Good Product Rejected+Defective Product Rejection Rate
~ Units/Day
~ |

Fixing=
min(Rejects.Gross Completion Rate * Fraction Rework in WIP)
~ Units/Day
~ |

Fraction Reworked=
1
~ Dimensionless
~ Identifies what portion of production found to be defective is then reworked.
|

Scrapping=
Final Rejection Rate 2 * (1 - Fraction Reworked)
~ Units/Day
~ Some fraction of rejects are immediately scrapped.
|

Rework=
Final Rejection Rate 2 * Fraction Reworked
~ Units/Day
~ |

Desired Work in Process=
Scheduled Gross Completion Rate*(Normal Processing Time* Initial Expected Process Yield + Normal Processing Time * (1 - Initial Expected Process Yield) * Fraction of work redone) * Ratio WIP Held to Required
~ Units

~ The desired level of WIP is determined by the desired gross completion rate and the normal processing time for completing units multiplied by the ratio of WIP held to Required.
|

Gross Completion Rate=
min(Potential Completion Rate from Resources,
min(Desired Gross Completion Rate,Normal Completion Rate))
~ Units/Day
~ The gross completion rate is the minimum allowed by either the available resources or the normal completion rate, or the backlog of orders.
|

Perceived Process Yield= INTEG (
Change in Perceived Process Yield, Initial Expected Process Yield)
~ Dimensionless
~ The expected process yield is an exponential smoothing of the past process yield.
|

Initial Defective Fraction WIP= REINITIAL(
((1 - Prob Rej Good Material) * (1 - Defective Fract in incoming materials
) * Probability of Defect Introduction + Prob Accept Bad Material * Defective Fract in incoming materials)/((1-Prob Rej Good Material)*(1-Defective Fract in incoming materials)+Prob Accept Bad Material*Defective Fract in incoming materials))
~ Dimensionless
~ The defective fraction in WIP is the amount of defective product in WIP divided by the total amount in WIP. The defective product in WIP is determined by the number of bad accepted into WIP plus the number of good product made bad while in process. The number of bad accepted into WIP is the defective fraction multiplied by the prob of accepting bad material. The number of good product made bad while in process is equal to one less the defective fraction multiplied by one less the prob of rejecting good material multiplied by the probability of defect introduction. The total WIP is the good accepted plus the bad accepted. The good accepted is one less the defective fraction multiplied by one less the prob of rejecting good material. The bad accepted is the defective fraction multiplied by the prob of accepting bad material.
|

Initial Def WIP = Initial WIP * Initial Defective Fraction WIP
~ Units
~ Initial defective WIP is the fraction of WIP that is defective multiplied by the total initial WIP.
|

Initial WIP = INITIAL(Desired Work in Process)
~ Units
~ Initial WIP is set at the desired level.
|

WIP Adjustment = (Desired Work in Process-Work in Process)/T to Adjust WIP
~ Units/Day
~ The firm seeks to adjust the WIP to desired levels over a time to adjust WIP.
|

Initial Expected Process Yield = (1 - Initial Defective Fraction WIP) * (1 - Prob Rej Good Product) + (Initial Defective Fraction WIP) * Prob Accept Bad Product
~ Dimensionless
~ The initial expected process yield is set to start the model in equilibrium. The fraction of processed units that will be accepted as good, will be equal to the fraction that are good and are accepted as good plus the fraction that are bad and are accepted as good.
|

Change in Perceived Process Yield=
(Process Yield-Perceived Process Yield)/T to Perceive Process Yield
~ 1/Day
~ The change in the expected process yield is determined by the gap between the process yield and the previous value of the expected process yield over the time required to perceive changes in the process yield.
|

T to Perceive Process Yield =7
~ Day
~ The amount of time it takes to perceive changes in the process yield.
|

Defect Density WIP = zidz(Defective Work in Process,Work in Process)
~ Dimensionless
~ The fraction of WIP which is defective.
|

Gross Defective Completion Rate =Gross Completion Rate*Defect Density WIP
~ Units/Day
~ The number of units completed multiplied by the fraction of total units which are defective.
|

Prob Rej Good Product = 0.005
~ Dimensionless
~ Probability of rejecting (scrapping) a good unit.
|

Net Defective Completion Rate = Gross Defective Completion Rate-Defective Product Rejection Rate
~ Units/Day

~ The number of defective units discovered prior to shipment. Equals the gross defective units completed less the defective product discovered (rejected).
|

Defects introduced = (Net Prod Start Rate - Defective Material into Process)
* Probability of Defect Introduction
~ Units/Day
~ These are good units made defective by handling or processing. They are equal to the number of good units started multiplied by probability of defect introduction. Defects can only be introduced into material that is originally good.
|

Defective Product Rejection Rate = Gross Defective Completion Rate*(1-Prob Accept Bad Product)
~ Units/Day
~ The number of defective material completed that is discovered and rejected. It equals the gross defective completion rate multiplied by one less the probability of accepting a bad unit.
|

Prob Accept Bad Product = 0.05
~ Dimensionless
~ The testing probability of accepting a bad unit.
|

T to Adjust WIP = 14
~ Day
~ The number of days it takes to adjust the WIP to desired levels.
|

****
.productionpd
**********~
|
Potential Completion Rate from Resources 0=
Labor Resource Capacity 0
~ Units/Day
~ The completion rate due to resources will be a function of available capital and labor. For testing purposes, it is a very large constant which will not limit the production start rate. Eventually this will become a Leontief production function of effective labor (where effective labor is based on productivity and the amount of labor) and capital as productive inputs (i.e. Min(potentialoutput from effective labor, potential output from capital))
|
Average Age of New Designs=
Age of New Designs / New Designs
~ Day

```
        ~               |

Defect Density Phase 3 WIP=
         zidz(Defective Work in Process 0,WIP Phase 3)
        ~       Dimensionless
        ~       The fraction of WIP which is defective.
        |

Effort to Phase 2=
        min( WIP Phase 2 / Normal Processing Time per Phase , Potential Completion Rate All
Phases\ * (WIP Phase 2 / Total Wip PD))
        ~       Units/Day
        ~               |

Effort to Phase 3=
        min( WIP Phase 3 / Normal Processing Time per Phase , Potential Completion Rate All
Phases\ * (WIP Phase 3 / Total Wip PD))
        ~       Units/Day
        ~               |

Design Initiatiation=
        Desired Net Production Start Rate 0
        ~       Units
        ~               |

Potential Completion Rate All Phases=
        Potential Completion Rate from Resources 0 * Number of Phases
        ~       Units/Day
        ~       The potential completion rate from any one phase, if all effort were \
                placed there, is equal to the average completion rate possible multiplied \
                by the number of phases.
        |

WIP Phase 3= INTEG (
        Second Handoff-Gross Completion Rate 0, Initial WIP 0 / Number of Phases)
        ~       Units
        ~       Number of units in process waiting to be completed.  Initially, is equal to the
desired level of work in process.  The change is determined by the net material start rate less the
gross completion rate in a given time period.
        |

Effort to Phase 1=
        min( WIP Phase 1 / Normal Processing Time per Phase , Potential Completion Rate All
Phases\ * (WIP Phase 1 / Total Wip PD))
        ~       Units/Day
        ~               |
```

WIP Phase 1= INTEG (
Design Initiatiation-First Handoff,
Initial WIP 0 / Number of Phases)
~ Units
~ |

Second Handoff=
Effort to Phase 2
~ Units/Day
~ |

Total Wip PD=
WIP Phase 1 + WIP Phase 2 + WIP Phase 3
~ Units
~ The total designs in the three phases.
|

First Handoff=
Effort to Phase 1
~ Units/Day
~ |

Number of Phases=
3
~ Dimensionless
~ The number of general phases in the design process (3 produces a 3rd order delay which is meant to represent the proper transient response).
|

Initial WIP 0= INITIAL(
Desired Work in Process 0)
~ Units
~ Initial WIP is set at the desired level.
|

WIP Phase 2= INTEG (
First Handoff-Second Handoff,
Initial WIP 0 / Number of Phases)
~ Units
~ |

Normal Processing Time per Phase=
Normal Processing Time 0 / Number of Phases
~ Day
~ |

```
Desired Net Production Start Rate 0 =
max(0.Scheduled Gross Completion Rate 0+WIP Adjustment 0)
        ~       Units/Day
        ~       The desired number of units flowing into WIP as determined by the desired
completion rate and the adjustment for any shortfalls in WIP.
        |

Desired Work in Process 0=
        Scheduled Gross Completion Rate 0*Normal Processing Time 0
        * Ratio WIP Held to Required 0 * Number of Phases
        ~       Units
        ~       The desired level of WIP is determined by the desired gross completion rate and
the normal processing time for completing units multiplied by the ratio of WIP held to Required.
        |


Net Completion Rate 0 = Gross Completion Rate 0-Final Rejection Rate 0
        ~       Units/Day
        ~       The number of units shipped is equal to the total finishing rate less the
                final scrap rate.
        |

Scheduled Gross Completion Rate 0=
        min(Desired Gross Completion Rate 0, Potential Completion Rate from Resources 0)
        ~       Units/Day
        ~       This keeps the production line from starting at a faster rate then they
                could complete units.
        |

Desired Net Completion Rate 0= GAME (
        Suggested Net Completion Rate 0)
        ~       Units/Day
        ~       The required number of units required by downstream processes/customers (order
backlog) in units per day.
        |


**********************************************************
        .NPT
**********************************************************~
        |
Ratio WIP Held to Required 0=
        attribute(Initial WIP control 0,
        T to Erode WIP Control 0*Days Per Year , Minimum WIP to Required 0,
        WIP Control Half Life 0, Adequacy of NPT Improvement Effort 0)
```

~ Dimensionless
~ The ratio of desired WIP held in the system to that absolutely necessary to doing business.
|

Normal Processing Time 0=
max(TIME STEP,attribute(Initial Normal Processing Time 0,
T to Erode Processing Time 0*Days Per Year , Minimum Processing Time 0,
Processing Time Improvement Half Life 0, Adequacy of NPT Improvement Effort 0))
~ Day
~ Minimum time to process because of logistical constraints
|

****
.PDI
**********~
|
Probability of Defect Introduction=attribute(Initial Probability of Defect Introduction,
T to Erode Probability of Defect Introduction *Days Per Year, Limit Probability of Defect Introduction, Probability of Defect Introduction Improvement Half Life,
Adequacy of PDI Improvement Effort)
~ Dimensionless
~ The percent of units into which no defect is introduced during processing. (Note: This is not the observed yield out of WIP. This will be higher since the yield out of WIP is also lowered by defective raw materials).
|

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